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AN ANALYSIS OF SMOKE TRANSMITTANCE MEASUREMENTS AND TECHNIQUES

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November 1977

USA ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
USA BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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The Ballistic Modeling Division has made transmittance measurements at selected regions of the electromagnetic spectrum through various aerosols in field environments. The measurements have been obtained with visual, near infrared, far infrared, and millimetre wave instrumentation. Live firings were conducted at Fort Sill, Oklahoma, using mortar- and artillery-delivered hexachloroethane (HC) and white phosphorous (WP) munitions. At Fort Hood,

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20. ABSTRACT (Continued)

Texas, 2.75-inch rockets were launched from helicopters to deliver WP wick-produced smoke. The smoke testing has also included HC and fog oil smoke pots as well as red phosphorous grenades launched from vehicles. The aerosol testing has included measurements through both smoke and dust clouds. A discussion of the tests, the spectral regions measured, the equipment used, the type of data collected, and an analysis of the results are presented.

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I. INTRODUCTION

Smoke has been employed tactically in warfare for centuries. Waring factions in India dating back to 2000 B.C. are said to have used incendiaries and smoke screens. The first recorded use of smoke as a screening agent was in 1701 when Charles XII of Sweden burned damp straw at a river crossing to conceal troop movements. Until World War I, smoke was generally thought to be more of a liability than an asset. After the successful use of smoke screens by the Germans at the Battle of Jutland in 1916, both the Allies and Germans developed screening smokes during World War I.

During World War II smoke screens were used extensively by both land and naval forces. Smoke-producing aircraft and boats provided screens during air attacks and amphibious landings. Underwater demolition teams and tactical maneuvers of ground troops were concealed through the use of smoke screens. The development of smoke projectiles for use by indirect-fire weapons systems permitted the use of smoke beyond the immediate battle area for the purpose of preventing enemy observation of front-line troops. Smoke was also used as a decoy to deceive the enemy into thinking that a buildup of troops and material was occurring when it actually was not. The use of smoke was very limited during the Korean and Vietnam conflicts, being used primarily as a marking agent. The United States' interest in the use of smoke was rekindled as a result of the recent Israeli/Egyptian conflict when smoke was used in an attempt to decrease the effectiveness of the anti-tank guided missiles (ATGM).

Since smoke proved an effective countermeasure against the optical sights of the ATGM's, questions arose as to the effectiveness of the use of smoke against electro-optical devices in general. With the United States developing more and more sophisticated electro-optical instruments, any technique which could be used to neutralize or reduce their effectiveness would be of great interest.

Some of the optical devices in current use by the military which could be adversely affected by smoke include telescopes, binoculars, artillery and mortar sights, aiming circles, rangefinders, and one of the most important - the human eye. Electro-optical devices of interest include image intensifiers, lasers used as rangefinders and designators, thermal imaging devices, orthicons, vidicons, TV guided missiles, guided missiles with near infrared guidance links, and infrared seeking missiles.

II. BACKGROUND

The Ballistic Modeling Division (formerly Concepts Analysis Laboratory) of the Ballistic Research Laboratory was tasked to provide instrumentation for obtaining transmittance measurements at various wavelengths through smoke at a test to be conducted at Fort Sill, Oklahoma, in December 1975. After discussions with the test directors, non-coherent sources rather than laser sources were deemed more suitable for this test. There were three main reasons for not selecting lasers as the primary energy source. First, the main purpose of the transmittance measurements was to obtain quantitative data which would be compatible with broad-band devices (i.e., the human eye, thermal imaging devices, etc.). Since lasers are very narrow band, broad-band sources with broad-band receivers containing appropriate filters were selected. Second, it was thought that the long path lengths (up to 1500 metres) with the line of sight very close to the ground would cause too much undesirable scintillation of the laser beam. Third, the use of lasers would undoubtedly cause many safety problems. If safety goggles were used, the goggles would affect the sight of the human observers who were to serve as data collection sensors. In addition, the lasers available to the Ballistic Modeling Division (BMD) personnel had not proven field worthy under dusty conditions. The non-coherent sources chosen, an automotive spotlight and a standard high-temperature black body radiator, were simple, rugged, eye-safe items.

The discussions with the test directors led to the decision to make transmissometers to supplement human observers, devices operating in the near infrared, and thermal viewers operating in the far infrared.

Figure 1 shows transmittance through the earth's atmosphere for the visible and infrared portions of the electromagnetic spectrum.[1] The variation of transmittance with wavelength is normally due to the absorption by the water vapor and carbon dioxide in the atmosphere. Most systems are designed to operate in "atmospheric windows" where absorption by the atmosphere is not severe.

Also shown in Figure 1 are bars indicating the portions of the spectrum in which the transmissometers were designed to operate. The transmissometers to supplement the human observers operate from about 0.4 micrometres to about 0.7 micrometres. The devices, such as some night sights and missile guidance links (and likewise the corresponding transmissometer), which operate in the near infrared use wavelengths in the 0.7 to 1.1 micrometre band. Some thermal imaging devices operate in the 3 to 5 and 8 to 14 micrometre bands; thus transmissometers were designed for response in the same regions.

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[1] Wolfe, William L., Handbood of Military Infrared Technology, 1965.

III. AEROSOLS

The smokes tested at Fort Sill were the current inventory of HC (hexachloroethane) and WP (white phosphorous) munitions. Both of these smokes are hygroscopic and nucleate available atmospheric water vapor, producing an artificial fog. The water droplets which are formed on the hygroscopic nuclei scatter the radiant energy impinging on them and thus attenuate the energy source (whether it be from the natural environment or man-made).[2,3]

Figure 2 shows a histogram which describes the radius distribution of the scattering particles for phosphoric acid, the hygroscopic smoke component for WP munitions.[4] The particle size distribution for the components of the other smoke inventory munitions, including HC and fog oil, is comparable to that of phosphoric acid. Generally most of the smoke particles are of radii less than 0.5 micrometre.

Another aerosol which was part of the Fort Sill test, as well as subsequent smoke tests, was dust. Dust clouds were created by the projectiles impacting the ground and also by vehicles traveling in the impact area. Dust typically presents a wide range of particle sizes, as can be noted in Figure 3. The dust, from which the data in Figure 3 was derived, was produced by M48 tanks.[5] The dust particle sizes, unlike the smoke particle sizes, span the infrared wavelength region of interest as well as the visible area. Dust particles of about 1 micrometre and smaller do not undergo gravitational fallout but remain airborne.

The data of Figure 3 were obtained at two different ranges in the Fort Knox, Kentucky, area. The particle size distributions from the two ranges are essentially identical. About 45 percent of the particles (by weight) have diameters less than 15 micrometres, as is indicated on the figure. The predominant diameter is estimated at 17 micrometres.

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[2]Engineering Design Handbook - Military Pyrotechnics Series Part One - Theory and Application, AMCP 706-185, April 1967.

[3]Engineering Design Handbook - Military Pyrotechnics Series Part Four - Design of Ammunition for Pyrotechnic Effects, AMCP 706-188, March 1974.

[4]Allen, George (CPT) and Simonson, Bernard, E., "Attenuation of Infrared Laser Radiation by HC, FS, WP, and Fog Oil Smokes," Edgewood Arsenal Technical Report No. 4405, May 1970.

[5]Engineering Design Handbook - Environmental Series Part Three - Induced Environmental Factors, AMCP 706-117, January 1976.

Dust samples taken from various geographical sites on the earth exhibit particle sizes up to 150 micrometres with the percentage by weight for particles larger than 74 micrometres reaching a high of 55 percent. Many localities other than desert areas experience moderate to heavy dust conditions. It is even possible for tropical areas such as Vietnam to produce a dusty environment under heavy traffic conditions during dry periods.

The dust aerosols, as well as the smoke aerosols, can attenuate electromagnetic radiation and greatly affect the performance of optical systems.

IV. INSTRUMENTATION

The instrumentation, which was initially used for the Fort Sill smoke tests, was intended to provide quantitative data to supplement devices of a qualitative nature. The devices which needed quantitative support instrumentation were the human eye, missile guidance links operating in the near infrared, and thermal imaging devices operating in the far infrared.

The human eye is the most numerous optical sensor to be found on the battlefield. In order to obtain quantitative data which would partially simulate what the eye would "see", two systems were developed - one to measure the transmittance of a white light source and the other to measure the contrast between two portions of a target.

Figure 4 shows the photopic response of the average human eye.[6] (Photopic vision refers to the response of the eye in a light adapted state and involves the cones in the retina of the eye. Scotopic vision refers to the response of the eye in a dark adapted state, and involves only the rods). The average eye can see radiation with wavelengths between about 0.4 and 0.7 micrometres. Any instrumentation used to obtain data to be compatible with the eye should be filtered so that the response of the device nearly matches that of the eye.

The 0.4 to 0.7 micrometre transmissometer is shown in Figure 5. The detector is a Pritchard telephotometer utilizing a two-minute-of-arc field of view and a 1P21 photomultiplier tube. The telephotometer uses a photopic filter which provides a system response as shown in Figure 6, along with a photopic response curve of the eye.[7] The light

[6] Electro-Optics Handbook, RCA, 1968.

[7] Photo Research Corp. - Pritchard Photometer Instruction Manual.

source is a 12-volt, automotive, high-intensity spotlight. Since the telephotometer will sense ambient visual light, a two-per-second chopper disc is used to differentiate the light source signal from ambient light.

A sample of simulated data from this system is shown in Figure 7. The amplitude "a" represents the signal level for a clear or ambient atmospheric condition; amplitude "b" represents the signal level when there is smoke (or other aerosol) in the field of view. Using the amplitude "a" as the reference (clear) condition, the transmittance at the other atmospheric condition is simply

$$T = \frac{b}{a} \tag{1}$$

If the frequency component f is not present, there is no signal being received from the source. The amplitude "a" can also be used to determine when the atmosphere has returned to its ambient condition, as it was before the smoke was released.

The system used to measure contrast through the smoke cloud is shown in Figure 8. The detector is a Pritchard telephotometer with a photopic filter and a 1P21 photomultiplier tube. The distance between the source and detector was 1500 metres. With a two-minute field of view at that range, the telephotometer would be "looking at" a circle of 0.87 metre diameter at the source. The source is a 2.44-metre-diameter disc with four-quarter circle segments - two painted flat white and two painted flat black. As the disc rotates at a speed which can be varied continuously up to about two revolutions per second, the telephotometer measures the luminance of the white area and then the black area. The definition of contrast between two objects W and B is

$$C = \frac{B_B - B_W}{B_W}, \tag{2}$$

where C is the (luminance) contrast, B_B is the luminance of the object B and B_W is the luminance of the object W.[8] Figure 9 shows the type of data obtained with this system. Area 1 represents the clear air condition and 2 represents the smoke condition. The contrast between the objects W and B in the presence of smoke is given by

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[8]Middleton, W.E.K., Vision Through the Atmosphere, Toronto Press, 1958.

$$C_s = \frac{T\ (B_B - B_W)}{T\ \ B_W + B_C} \tag{3}$$

where T is the transmittance of the smoke cloud as determined above and B_C is the luminance of the cloud. The percent reduction in contrast is then

$$C_X = \left[1 - \frac{C_s}{C}\right] \text{ x } 100. \tag{4}$$

This procedure for determining contrast reduction applies only to the one point in time. This procedure must be repeated any place along the curve where the contrast reduction is desired. The frequency component f must be present to indicate a signal from the disc.

A second transmissometer, operating from 0.7 to 1.1 micrometres, was designed to obtain data in the same portion of the spectrum (near infrared) where some night sights and missile guidance links operate. The source is the same automotive spotlight used for the 0.4 to 0.7 micrometre measurements. The telephotometer, shown in Figure 10, consists of an 89mm-diameter Questar telescope as the collecting optics, with an aperature restricting the field of view to six minutes of arc. The image is focused on the sensitive surface of a 7102 photomultiplier tube. The addition of a Kodak 89B filter helps to provide the system response curve shown in Figure 11.

Another transmissometer was a dual detector device operating in the far infrared portion of the spectrum. The device, shown in Figure 12, consists of an infrared heat source, pyroelectric detectors, and associated electronics. The heat source is an Infrared Industries standard 1000°C blackbody source at focal plane of an 203mm-diameter, 1524mm focal length, Cassegrainian telescope. The telescope collimates the beam, thus permitting the beam to be propagated further through the atmosphere without as much dispersion as with simply a diffuse source. The temperature of the source can be accurately controlled and is continuously variable up to 1000°C. The beam is chopped at a rate of 240 times a second for enhancing signal processing. More detail about the signal processing will be given later. The spectral radiance of a 1000°C blackbody is shown in Figure 13.[9]

The receiver has a matching Cassegrainian telescope as collecting optics. The receiver incorporates a beam splitter which passes only the 8-14 micrometre portion of the spectrum, while reflecting the

[9]Engineering Design Handbook - Infrared Military Systems Part One, AMCP 706-127, April 1971.

3-5 micrometre portion. The received energy is focused on two Laser Precision, Incorporated, pyroelectric detectors, one detector for the 8-14 micrometre region and the other for the 3-5 micrometre region. The measurements in the 8-14 micrometre region were obtained to provide transmittance data for devices such as the AN/TAS 5 thermal night sight which operates in that spectral region. The 3-5 micrometre transmittance data were collected for compatibility with devices such as the AN/TAS 3 thermal night sight.

A synchronous detection signal processing technique was incorporated where the source was chopped at 240 hz and a reference chopping signal was transmitted by an FM telemetry link to the detector area. The detector and the source reference chopping signals were supplied to a lock-in amplifier, which measured the detector signal only when a reference pulse was received. By chopping at a high rate and integrating the output, a great improvement in signal-to-noise ratio was obtained. The data from all of the transmissometers were recorded on strip chart recorders.

V. AMSAA/FORT SILL SMOKE TEST

The test proponent of the smoke test held at Fort Sill, Oklahoma, in December 1975 was the Army Materiel Systems Analysis Activity (AMSAA). The purpose of the test was to provide data to AMSAA for use in validating their JTCG/ME smoke obscuration model, and to provide for assessment of the current doctrine and concept for the tactical employment of artillery and mortar-delivered smoke.

The delivery systems used in the test included 60mm, 81mm, and 4.2-inch mortar platoons and 105mm and 155mm howitzer batteries. The smoke agents included hexachloroethane (HC) and white phosphorous (WP). All of the firings were live, and the number of rounds varied from single to multiple volleys of each caliber. There were 139 missions conducted during the test, including both daytime and nighttime firings.

A diagram of the range is shown in Figure 14. The howitzers and mortars were fired from the south (right side of the figure) into the impact area, a distance of about 2000 metres. Camera coverage was provided by 35mm still cameras (with exposures every 15 seconds) at the positions marked OP1, OP3, OP4, OP6, and the bunker. Also located at the still camera positions were human observers who tape recorded their observations of the smoke cloud and target boards. A 16mm movie camera mounted in a helicopter provided overhead coverage. The camera coverage was to provide data on the growth and extent of the smoke cloud. Also located at OP1 was a crew-served-weapons sight. At OP3 were a TOW system and the BMD 0.4-0.7 micrometre transmissometer and contrast measuring instrumentation. The distance from the OP's to the sources in the impact area ranged from 1200 to 1600 metres, with the range to OP3 being 1500 metres.

In the bunker, in addition to the already mentioned human observer and camera personnel, were the forward observer, a DRAGON missile trainer system, an AN/TAS-3 thermal imaging system, an AN/TAS-5 thermal imaging system, low-light-level TV systems, and the BMD 0.4-0.7, 0.7-1.1, 3-5, and 8-14 micrometre transmissometers, as well as an M32 night sight and several hand-held thermal viewers. The distance from the bunker to the sources was 500 metres. The 0.4-0.7 micrometre transmissometer used at the bunker is shown in Figure 15 and was very similar to the one previously described. The detector was a Gamma Scientific telephotometer with a field of view of six minutes of arc and a response curve as shown in Figure 16. The data reduction process was the same as described for the first transmissometer.

Meteorological data - wind speed, wind direction, and temperature at 0.5, 4, and 16 metres elevation - were provided at three different locations around the impact area. Relative humidity measurements were made at the bunker area. During the extended firings an M60A1 tank maneuvered through the impact area after the fire mission was complete.

Figures 17 and 18 show the visual contrast and 0.4-0.7 micrometre transmittance as a function of time after shell impact. The curves followed one another well, and both functions appeared to be affected about equally due to the smoke. As a result of the Fort Sill test a general conclusion could probably be drawn that one or the other measurement could be made and that both measurements are probably not necessary. If one measurement were to be omitted, it undoubtedly would be the contrast measurement. The reasons for omitting the contrast measurement are that the disc requires much longer initial setup time (particularly if wind velocity is greater than 5 mph) and much longer daily setup time because disc must be secured with ropes when not in use, alignment of the disc with the telephometer is more difficult than with a light source, the initial cost is much greater, and the data reduction time is much greater.

Figures 19 through 27 show the data obtained from the instrumentation located at the bunker site. Each of the delivery types is represented, as well as both HC and WP agents, and nighttime as well as daytime missions. After inspecting the nine graphs, a general conclusion pertaining to a specific delivery type or smoke agent should be avoided because the test was of a live-fire nature. Since the firings were live, large shell dispersions were noted in some missions where more than one gun was used, between missions, and between delivery types. Unless the impact of shells with respect to the line of sight of the instrumentation is known, false conclusions could be made if only a few samples are used. Figure 28 is a table showing the maximum time at 0% transmittance for the various delivery types.

Figures 19 and 28 indicate that the 60mm mortar provided very minimal obscuration (even in the visual portion of the spectrum) as compared with the larger calibres. The shell impacts for Figure 19 were very close to the line of sight. The minimal obscuration undoubtedly occurs because the 60mm round contains less than a pound of WP as compared with about sixteen pounds in the 155mm shell. The short obscuration time is due also to the nature of the WP burning process. The WP agent burns very rapidly at a relatively high temperature, with a very prominent pillaring effect. The WP cloud generally appeared as a rather dense cylinder (not very large in diameter) of rapidly rising smoke. This general effect was noted for all of the delivery types of WP. Only WP smoke was delivered by mortars, whereas both WP and HC were delivered by the artillery pieces.

The greatest effect was produced by the 155mm WP, with the 4.2 inch mortars placing second. The 155mm WP shells, which contain about twice as much WP as any of the other rounds, were the only ones to cause the far infrared transmittance to go to zero. The 60mm and 81mm mortars appeared to be essentially ineffective in the infrared region.

Figure 23 shows both HC and WP being used in the same firing. The WP is for the purpose of providing a quick build-up of smoke and the HC for providing a more persistent smoke.

The data from a nighttime firing is shown in Figure 26. No obvious additional effects were noticed in the data as compared with the daytime firings. A note of possible importance to the nighttime use of smoke is that on an overcast night a person could become engulfed in smoke and not realize it unless he could sense it in his lungs. If smoke pots were used in place of mortars or artillery, noise would not be a factor for indicating the possible use of smoke.

The mortar and artillery pieces were located about 2000 metres south of the impact area. Because of the short range the artillery shells flew almost a straight line to the impact area. Because of the flat trajectory the artillery shells would hit the ground and bounce numerous times before finally stopping a hundred metres or more past the initial impact location. As a result, the initial impact would produce a dust cloud with the smoke being produced only in the area of the final resting place of the shell. Figure 27 is representative of this type of phenomenon with the first reduction in transmittance being attributed only to dust and dirt. The initial impact was near the line of sight of the instrumentation. The smoke from the rounds was produced about 100 metres from the line of sight and required about one and a half minutes for the wind to bring the smoke into the field of view of the instruments. The reduction in transmittance appeared to be nearly the same amount for all of the wavelengths being measured.

AMSAA is to publish a report giving the effectiveness and comparisons of the various delivery types and smoke agents as well as the results from the various other systems involved - including the DRAGON, TOW, and thermal imaging systems. An updated version on the tactics and use of smoke on the battlefield is forthcoming based on the results of this test.

VI. FORT HOOD SMOKE TEST

The test proponent of the smoke test held at Fort Hood, Texas, in March 1976 was the US Army Aviation Center. The purpose of the test was to determine ability of the 2.75-inch WP/wick smoke rocket to provide screening smoke.

As stated previously, the mortar and artillery WP smokes burned very rapidly, causing a pillaring effect and rapid dissemination of the smoke cloud. In order to produce a more slowly burning (controlled) smoke a WP-impregnated cotton wick scheme was devised. With the use of the wick configuration, burning times of three to five minutes were planned for the wicks.

The delivery system for the smoke was the 2.75-inch rocket fired from a hovering helicopter. Each rocket contains 4 pounds of WP. Eight firings with 24 to 59 rockets per firing comprised the test. The smoke area was several hundred metres long and about 50 metres deep. The firings occurred at dawn, noon, and dusk.

The instrumentation provided by the Ballistic Modeling Division included 0.4 to 0.7 micrometre, 0.7 to 1.1 micrometre, 3 to 5 micrometre, and 8 to 14 micrometre transmissometers. The contrast disc was also included; however, after the first firing a strong gust of wind damaged the disc beyond repairs which could be made during the remainder of the test. The distance between the sources and receivers was 1000 metres, as indicated in Figure 29.

Some thermal imaging equipment and cameras were located at an observation post about 1500 metres from the impact area and at an elevation of about 50 metres above the BMD receiver site. An armored cavalry platoon traveled a dirt road near the impact area to provide moving and hot targets.

Results from two of the firings from the Fort Hood test are shown in Figures 30 and 31. The test run for Figure 30 involved 55 rockets, with 14 rockets being fired in a sequence of 4 volleys over a 19-minute interval. (One rocket on the second volley did not fire). The far infrared was not blocked very long, but the visual portion of the spectrum was blocked for about 45 minutes and the near infrared for 42 minutes. For the run represented by Figure 31, 41 rockets were fired in a series of 3 volleys over an 8-minute interval. The 8-14 micrometre region was blocked for about 13 minutes, the 3-5 micrometre region for 17 minutes, and the visible and near infrared regions for more than 20 minutes. These lengths of time for total blockage are certainly of importance for the consideration of battlefield survivability or the deployment of thermal imaging systems or certain guided missile types. Both of these trials occurred near dawn on successive days with little or no wind. The entire path of 1000 metres between the sources and receivers was filled with smoke.

The initial reduction in transmittance in Figure 31 was due only to the armored cavalry platoon which traveled a dirt road about 50 metres from the sources. The smoke from the first volley of rockets was just to the right of the line of sight of the instruments, and the armored cavalry platoon was visible to the unaided eye. The infrared signals started returning to normal about two minutes after the initial volley, but then the smoke became the dominant factor and the signals decreased to zero. The maximum times for zero transmittance for the various spectral regions are listed in Figure 32 for the Fort Hood Smoke Test.

VII. VEHICLE SMOKE GRENADE TEST

On 26 May 1976 vehicle smoke grenade systems on the MICV and M113 vehicles were tested at Aberdeen Proving Ground, Maryland, to determine the screening effects of the United Kingdom L8A1 smoke grenades. The grenade dischargers had various angles between the tubes, ranging from 10 degrees to 25 degrees. The grenades were discharged about 30 metres from the vehicles. A diagram of the test area is shown in Figure 33.

The mission which exhibited the most effect was a salvo of 12 grenades with 10 degrees between the tubes. The transmittance data for that run is shown in Figure 34. The far infrared transmittance did not go to zero on any of the trials, but the visible and near infrared were blocked for about 4 minutes. The smoke system appeared to provide sufficient obscuration in the visible portion of the spectrum; however, its usefulness against guided missiles is questionable. With the smoke 30 metres from the vehicle, only three-tenths of a second maneuverability time would be available against a missile with a velocity of 100 metres per second. Against missiles using near infrared guidance links, even if the guidance link were broken by the use of smoke, the missile would be so close to the vehicle at the time of lost guidance command that the missile probably would hit the vehicle anyway. The closer to the missile launcher the smoke screen can be placed, the more effective will be the smoke screen.

VIII. OLD BOMBING FIELD TESTS

In June 1976 some smoke tests were conducted at the Old Bombing Field area, of the Aberdeen Proving Ground, Maryland, to determine the ability of smoke munitions to attenuate millimetre wave signals at 94 and 140 GHz. The munitions for the test included fog oil pots, HC pots, and statically detonated 155mm WP artillery shells.

A diagram of the test area is shown in Figure 35. The millimetre wave radars were located 1500 metres from their target, an M48 tank. The millimetre wave instrumentation was provided by the BMD millimetre wave team. The infrared devices would not operate at 1500 metres because of the water vapor content in the atmosphere which resulted in low visibility. The infrared receivers were moved closer to the sources, but because of terrain and safety limitations the receivers had to be at an angle of about 5 degrees from the line of sight of the millimetre wave devices, the BMD also provided 0.4 to 0.7 micrometre, 0.7 to 1.1 micrometre, 3 to 5 micrometre, and 8 to 14 micrometre transmissometers.

Data for the fog oil pots, HC pots, and 155mm WP artillery shells are shown in Figures 36, 37, and 38. There were nine fog oil pots and nine HC pots used in the pot tests and three 155mm shells in the shell tests. The configuration of pot and shell positions is indicated in Figure 35. The most significant result of the tests is that the millimetre wave devices were completely unaffected by any of the smokes involved. This result would certainly indicate a possible direction for future systems as a countermeasure to the smoke problem.

A side test was performed while the equipment was located at the Old Bombing Field. Because of the noticeable presence of dust and its effect on the transmittance of the various signals at both Fort Sill and Fort Hood, a "quick look test" involving dust was performed. A three-quarter ton pickup truck drove up and down a dirt path about 30 metres from and parallel to the line of sight between the sources and the millimetre wave devices. Three round-trips were made, and the resulting data are shown in Figure 39. The millimetre wave portion of the spectrum was completely unaffected by the dust. The visible through the infrared portions were drastically affected, with all the wavelengths measured being affected to approximately the same degree. (In the case of smokes the visible and near-infrared portions were affected much more than the far-infrared.) If reference is made again to Figure 3, it is understandable why the visible and infrared wavelengths are attenuated more nearly the same - the particle sizes found in vehicular produced dust clouds span the wavelength region between the visible and infrared portions of the spectrum. The particle-size distribution no doubt accounts for the fact that the visible wavelengths are attenuated more than the infrared wavelengths. Since this amount of attenuation was produced by one three-quarter-ton pickup truck in a "not really dusty" environment, a real dust problem could be envisioned by a convoy of several hundred vehicles traveling in a dusty environment.

IX. SUMMARY

The limited amount of testing of electro-optical devices in a smoke environment to date has demonstrated that certain devices can be drastically affected by the presence of the smoke aerosol. Under the proper conditions of the path length through the smoke and the density of the cloud, far-infrared radiation as well visual radiation can be totally attenuated for extended lengths of time. Thermal viewers also encounter the problem of thermal flux "washout" produced by the high temperature burning of particularly the white phosphorous munitions.

The wind speed and direction are critical parameters in smoke testing. If the smoke is blown from the area of the sources to the area of the receivers, as opposed to normal to the line of sight, there will be a much greater volume of smoke in the path and hence a much greater chance that the smoke will affect the device.

Further testing under proper conditions should clarify how much effect specific quantities and types of smokes can have on specific electro-optical devices. Possible counter-countermeasures, such as employing millimetre wave instrumentation, should be investigated.

X. ACKNOWLEDGEMENTS

Members of the U.S. Army Meteorological Team stationed at Aberdeen Proving Ground provided much needed support at the various smoke tests. They helped in the packing of the equipment for shipment, transporting the equipment to the test site, setting up and operating the instrumentation, and in the data reduction. Appreciation is given, in particular, to SP4 Ken Simington for his continual assistance during the many months that the smoke tests were being conducted.

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9. Engineering Design Handbook - Infrared Military Systems, Part One, AMCP 706-127, April 1971.

APPENDIX A - ILLUSTRATIONS

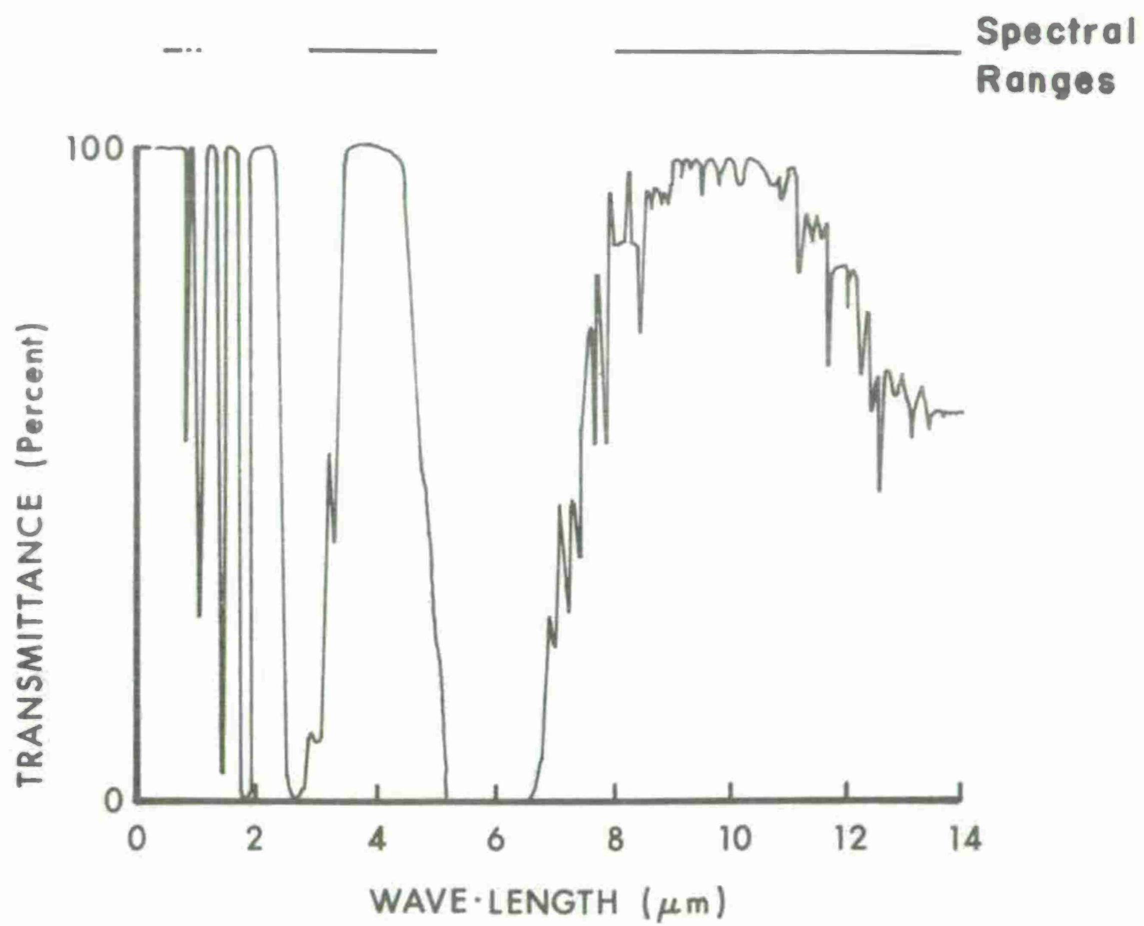

Figure I Atmospheric Transmittance and Spectral Ranges of the Transmissometers

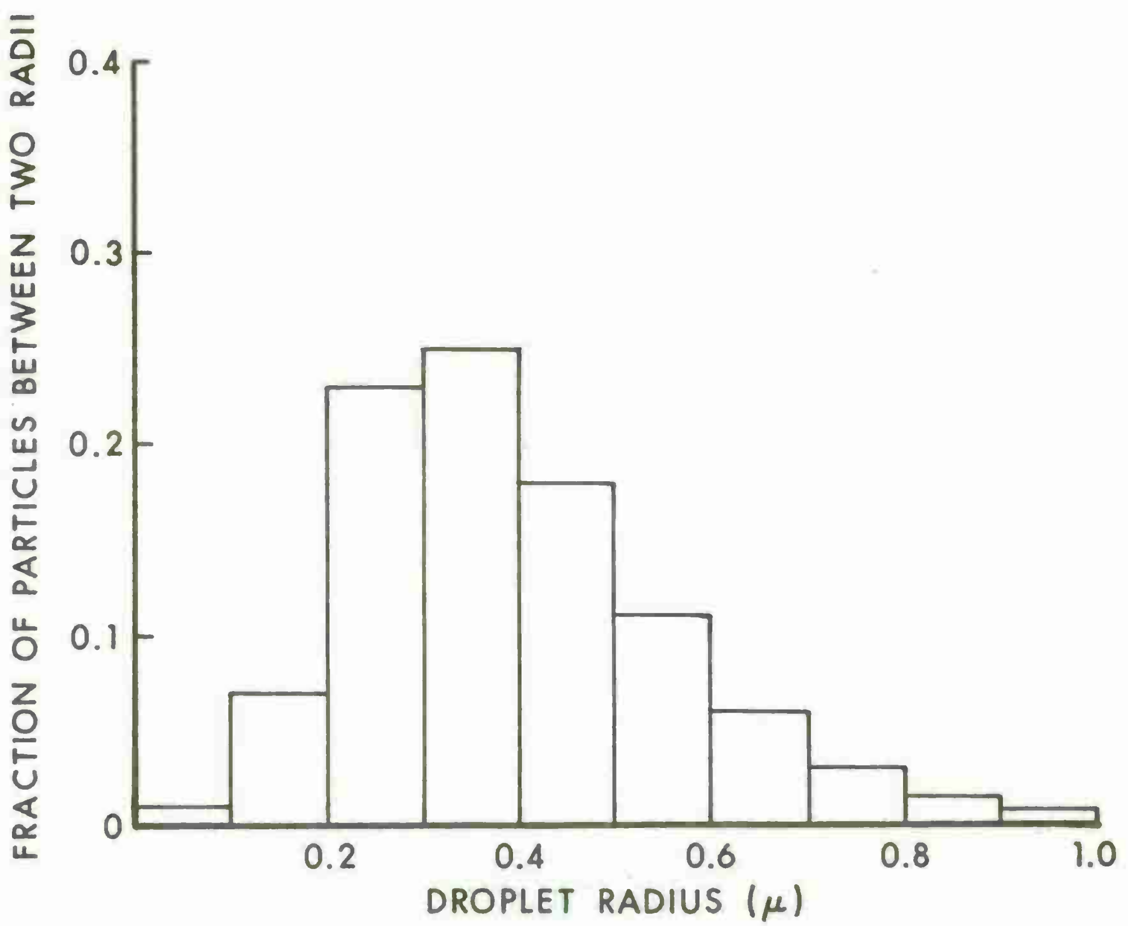

Figure 2 Radius Distribution for Phosphoric Acid (WP) Smoke

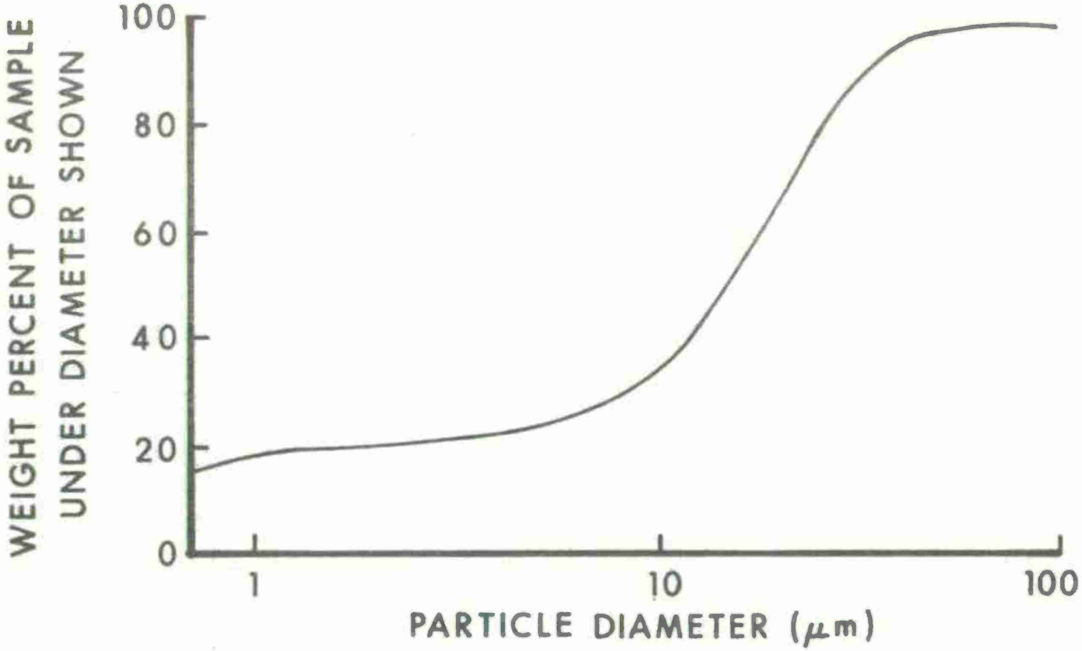

Figure 3 Particle Size Distribution of Dust Clouds Produced by Tanks

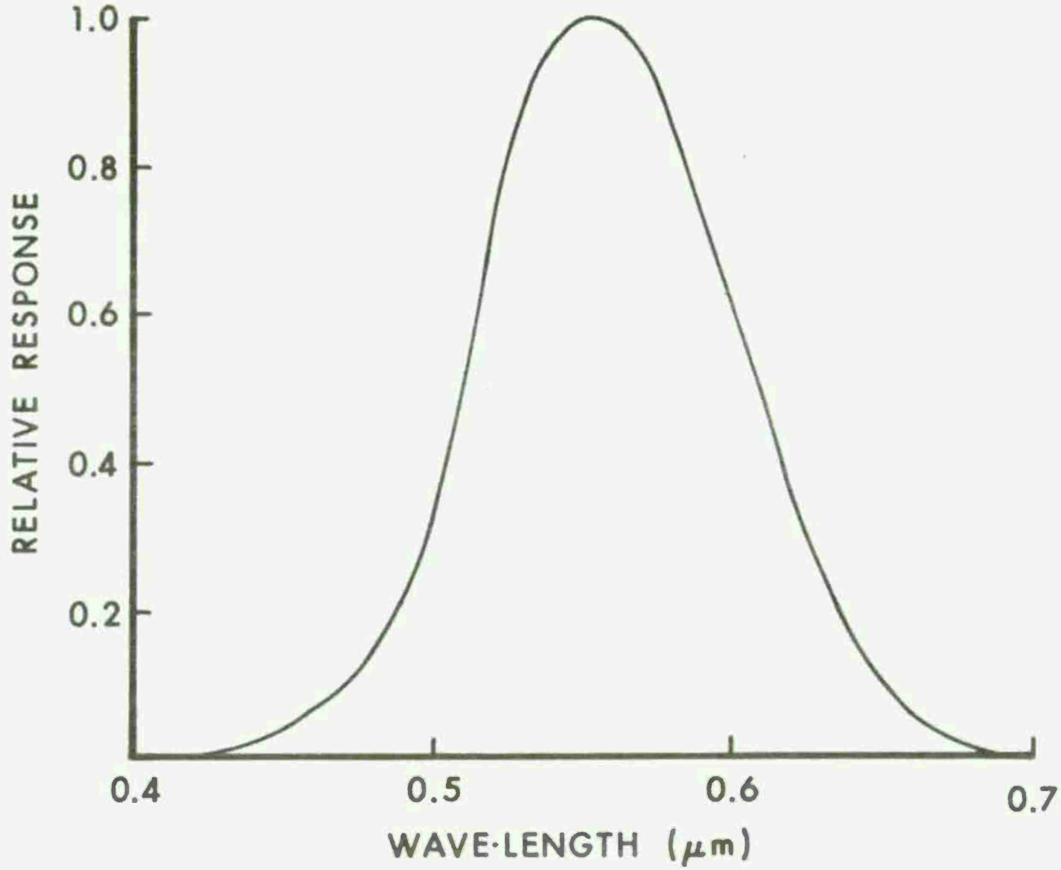

Figure 4 Relative Response Curve of the Human Eye to Radiation of a Given Wavelength

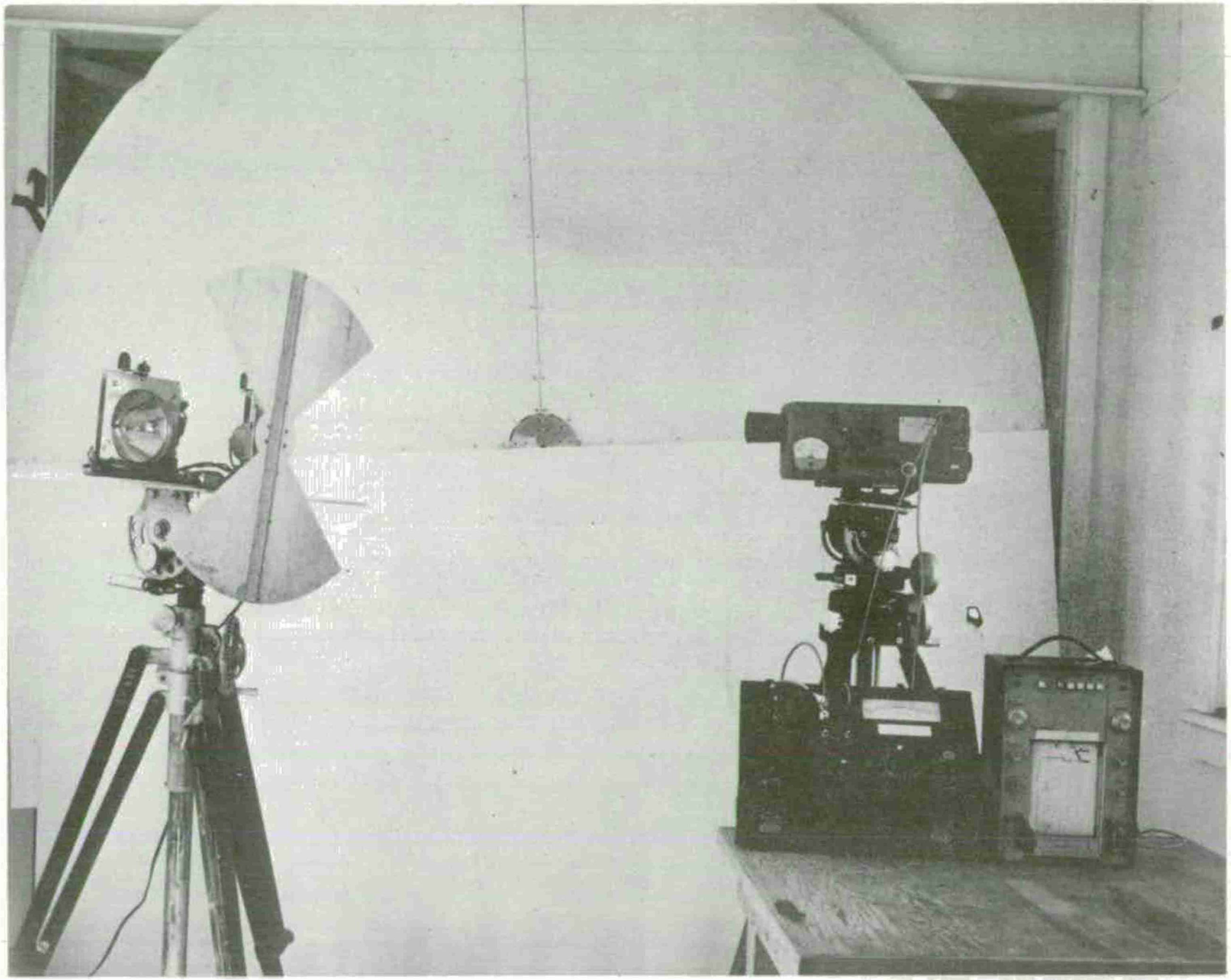

Figure 5 Photograph of 0.4 - 0.7 Micrometre Transmissometer

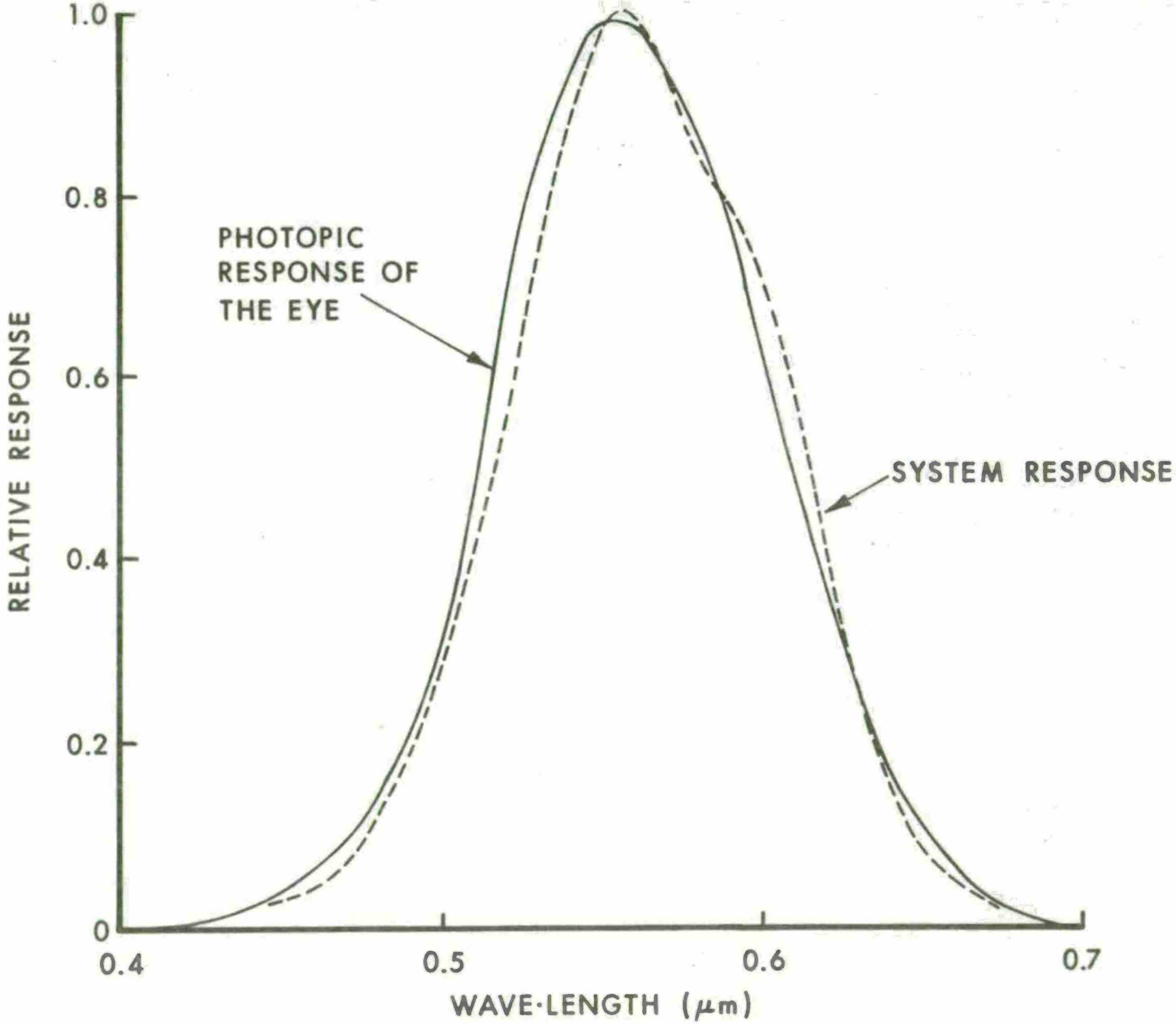

Figure 6 Relative Response Curve of the 0.4-0.7 Micrometre Transmissometer

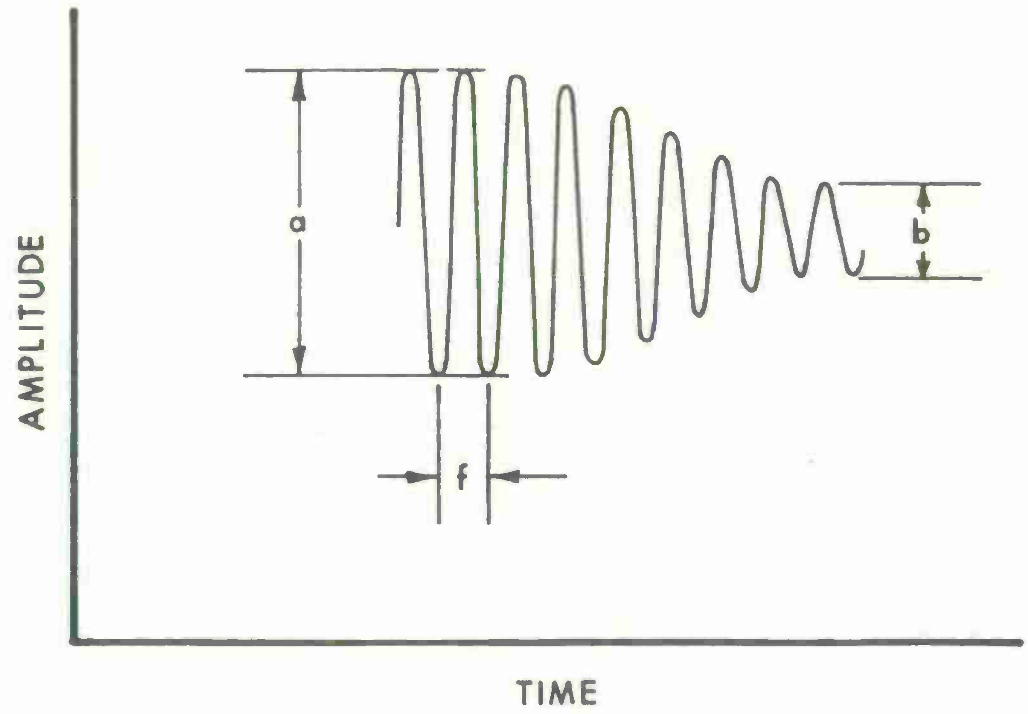

Figure 7 Simulated Data from Visual Transmittance Instrumentation

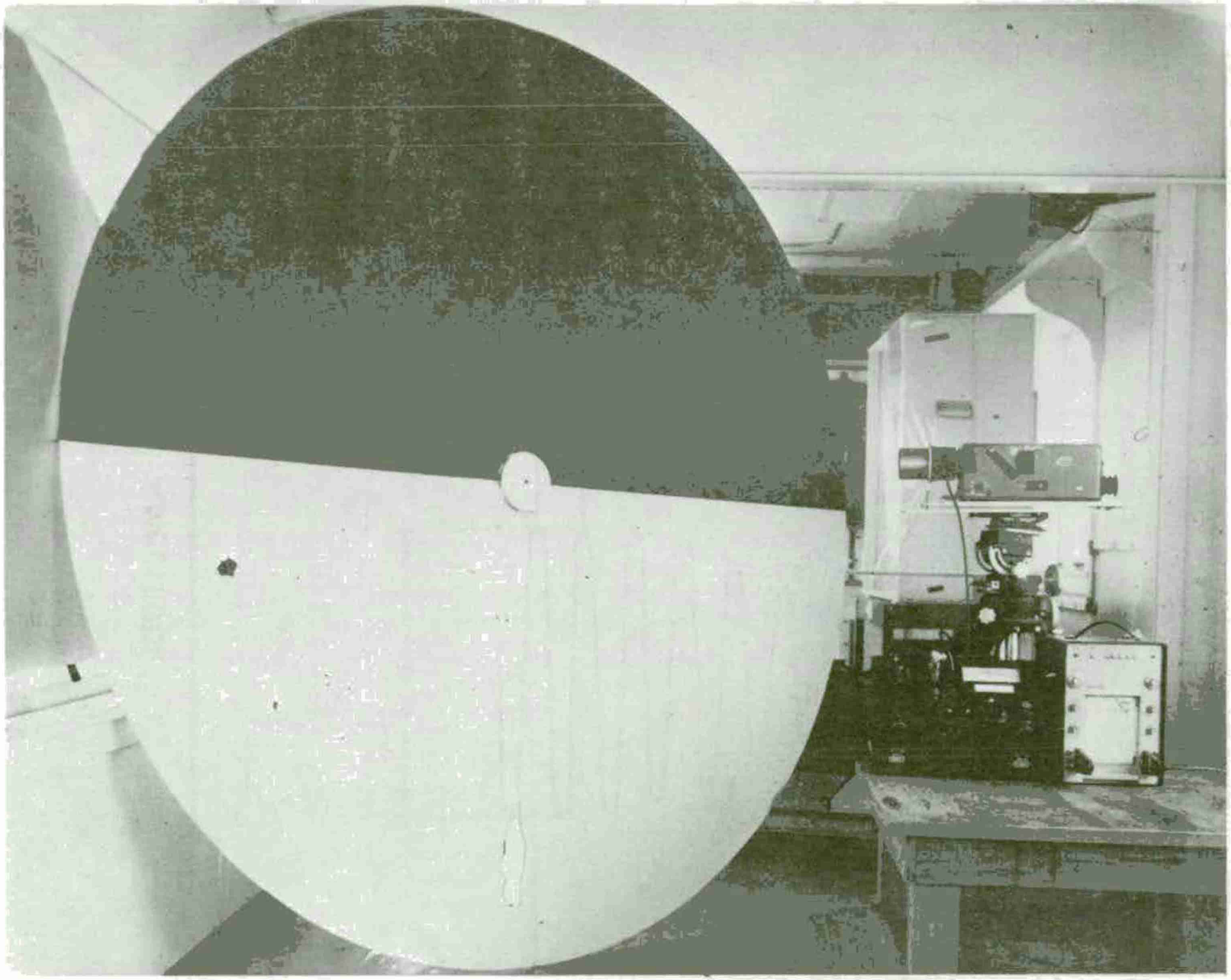

Figure 8 Photograph of Visual Contrast Measurement Instrumentation

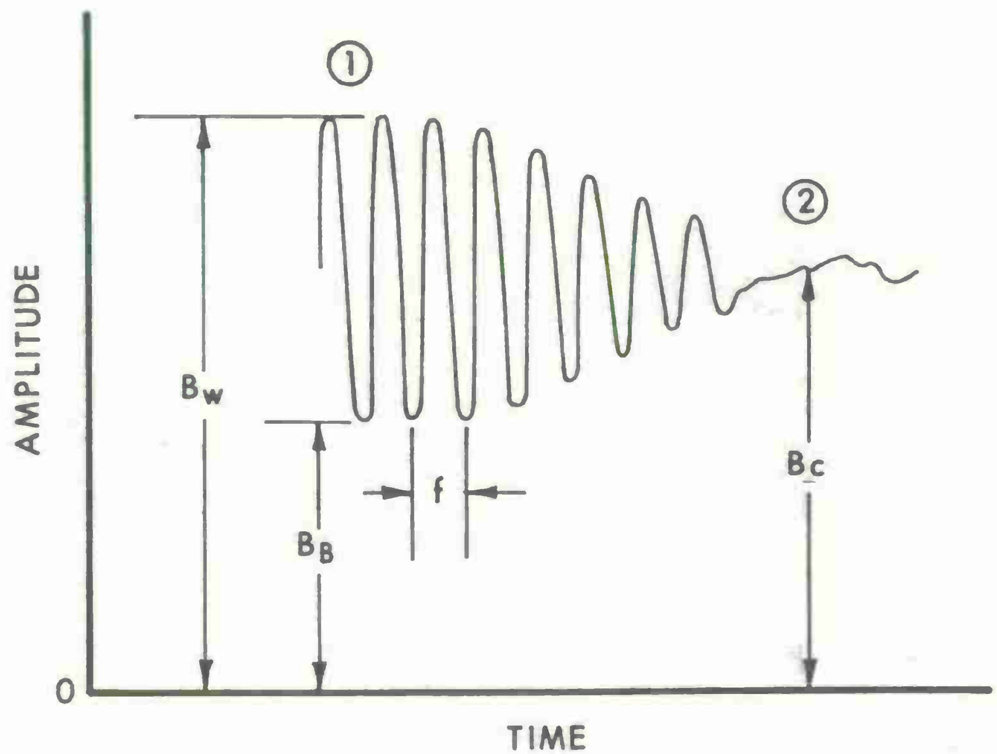

Figure 9 Simulated Data from Visual Contrast Measurement Instrumentation

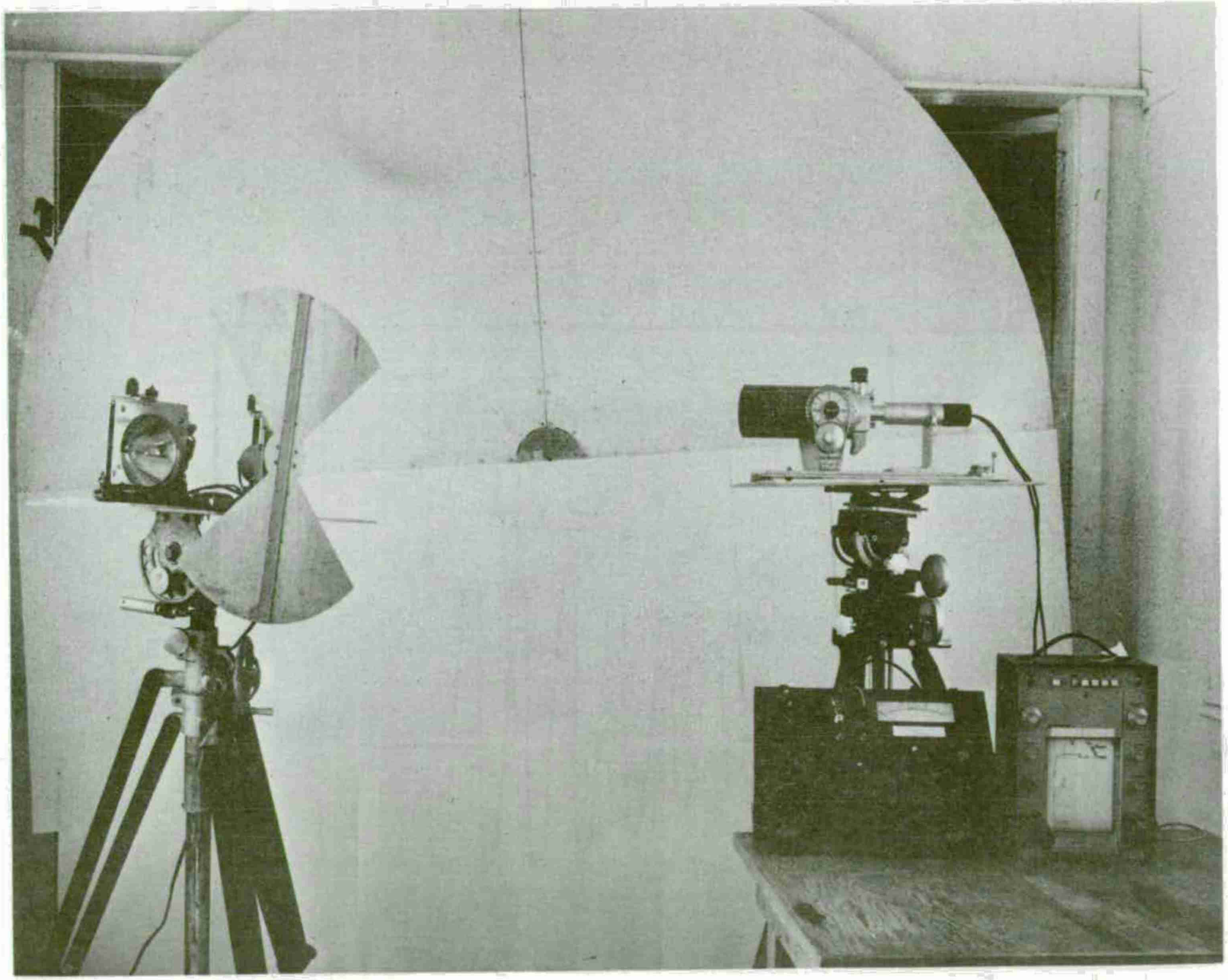

Figure 10 Photograph of 0.7-1.1 Micrometre Transmissometer

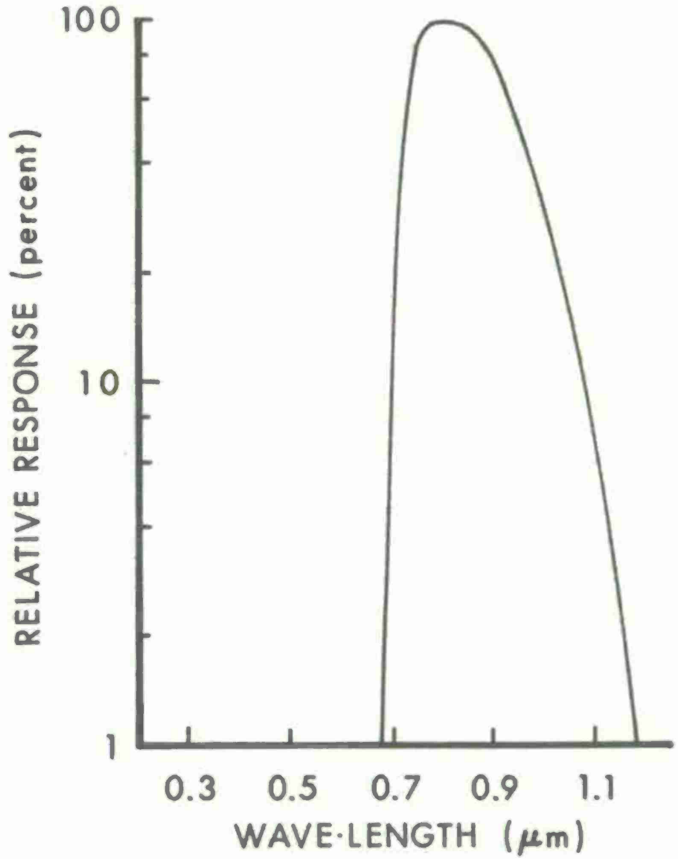

Figure 11 Relative Response Curve of 0.7-1.1 Micrometre Transmissometer

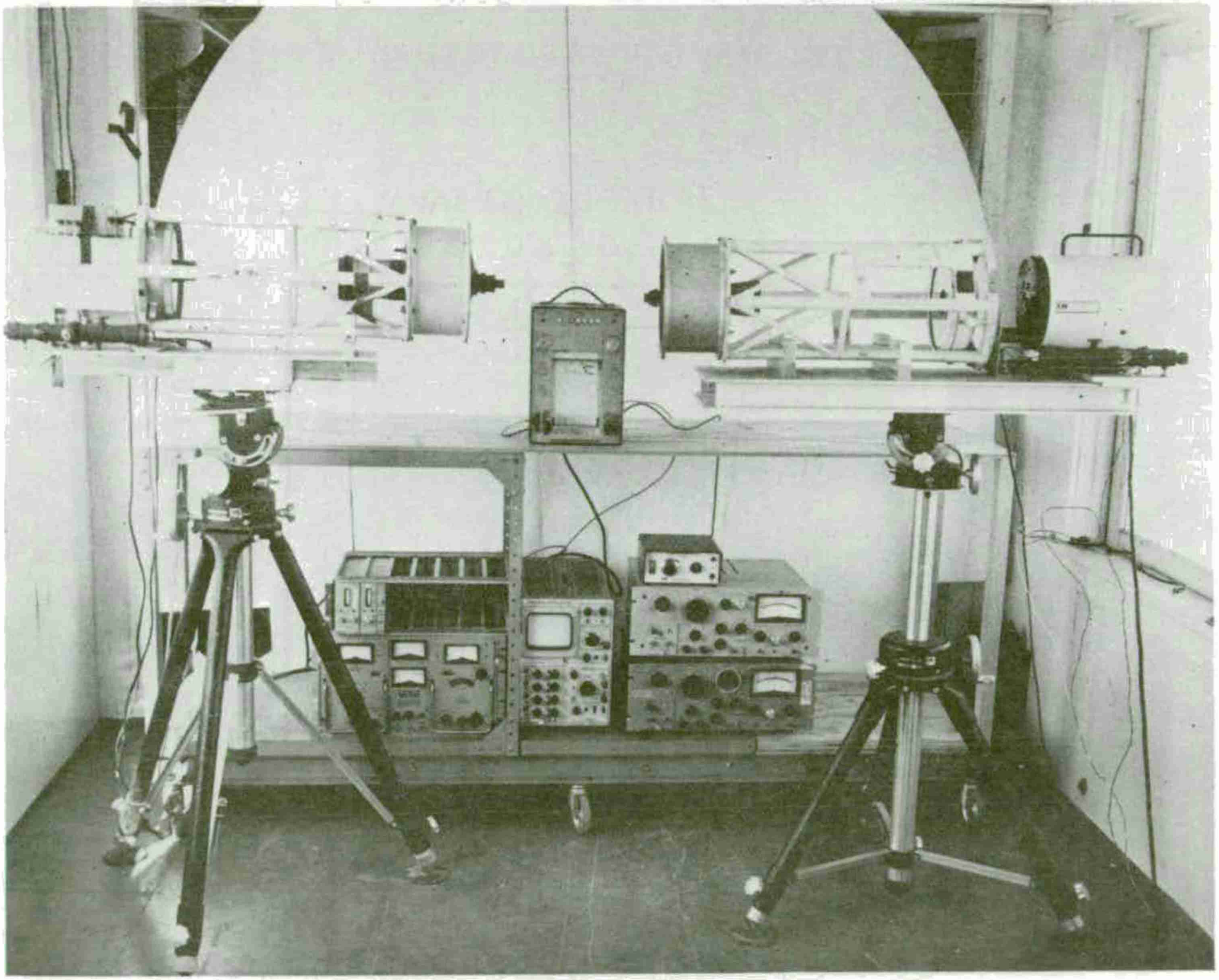

Figure 12 Photograph of 3-5 and 8-14 Micrometre Transmissometer

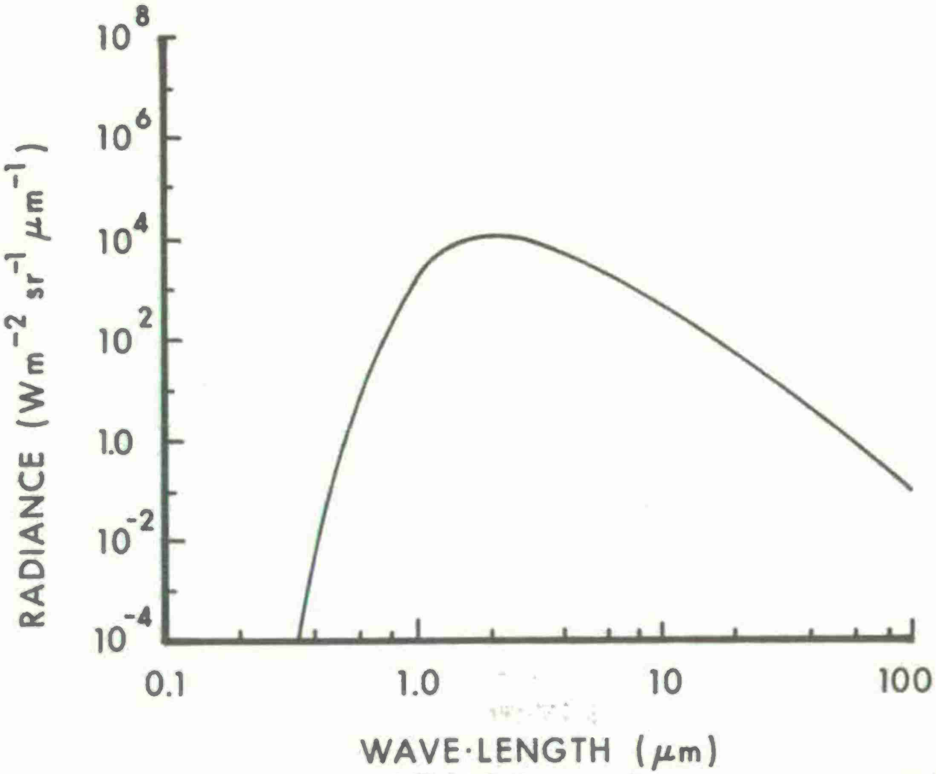

Figure 13 Spectral Radiance of a 1000° C Blackbody

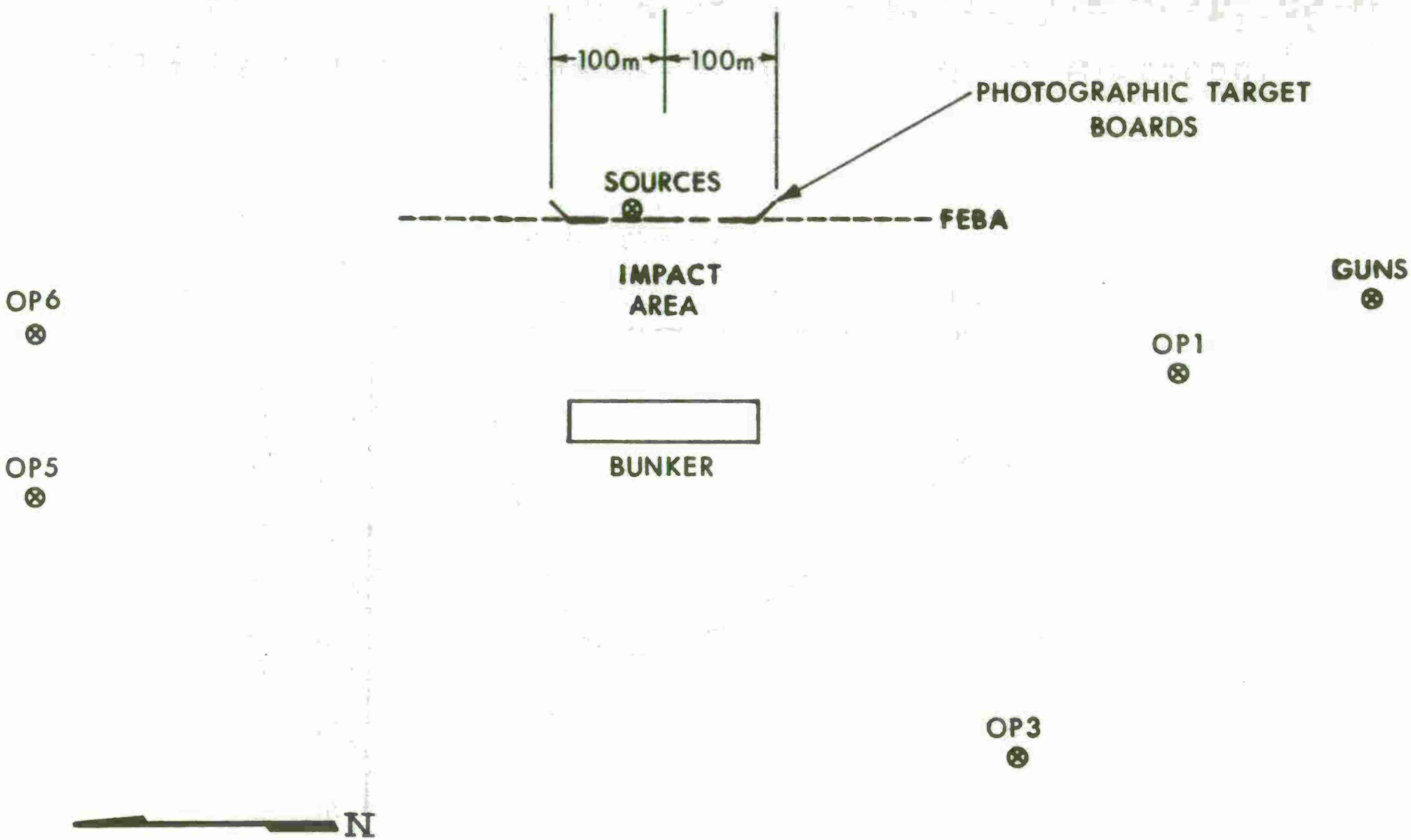

Figure 14 Diagram of the Fort Sill Test Range

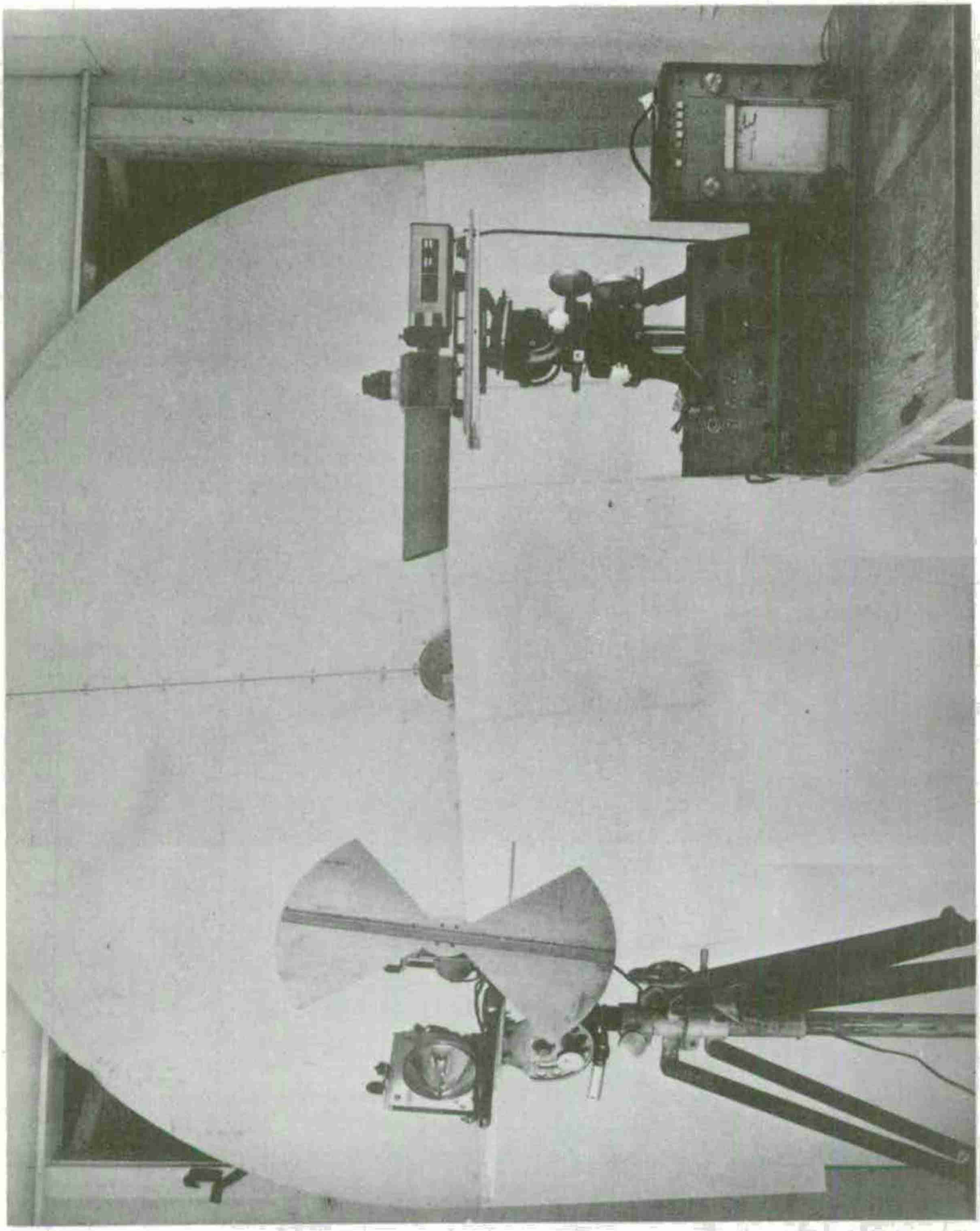

Figure 15 Photograph of 0.4-0.7 Micrometre Transmissometer II

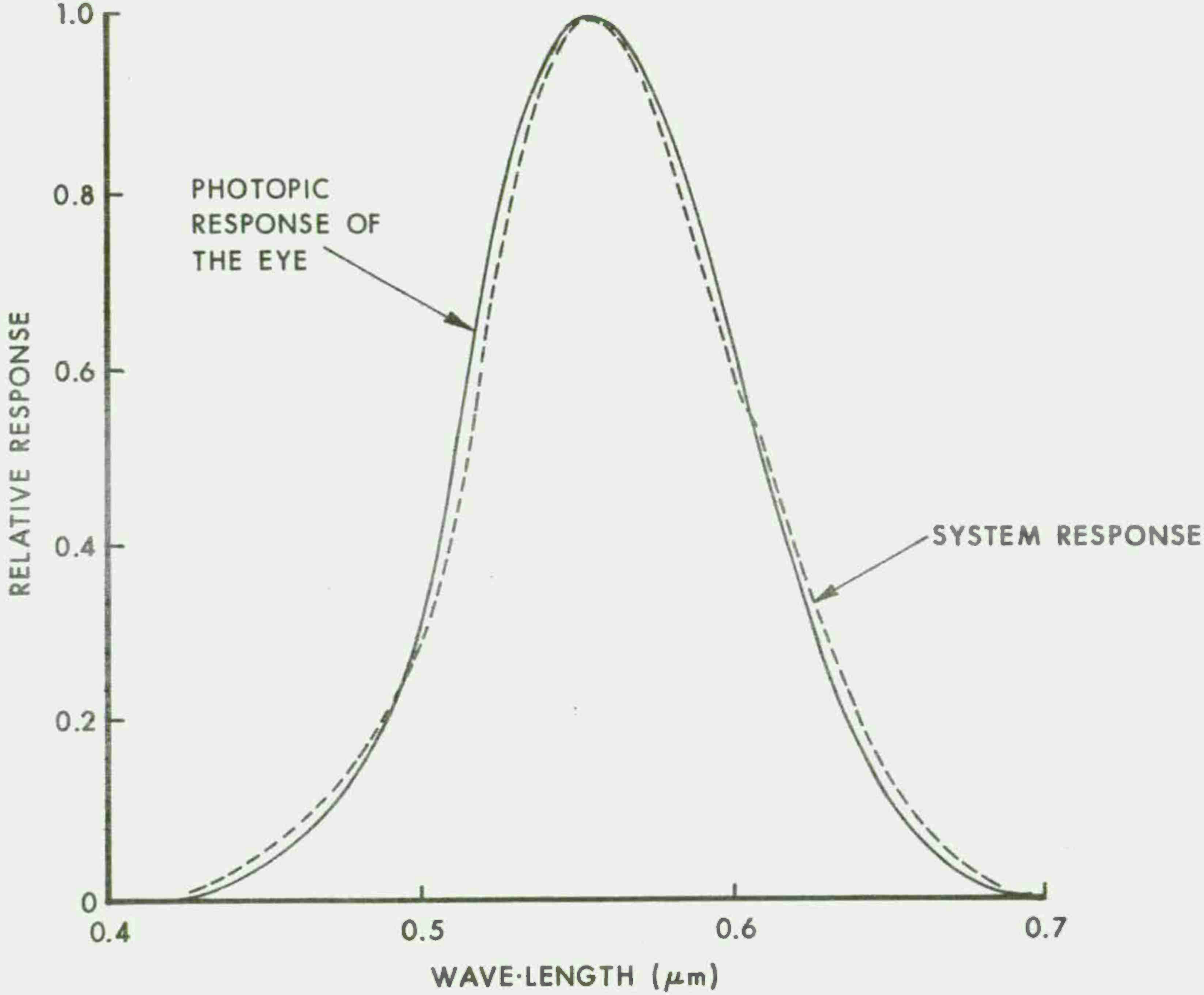

Figure 16 Relative Response Curve of 0.4-0.7 Micrometre Transmissometer II

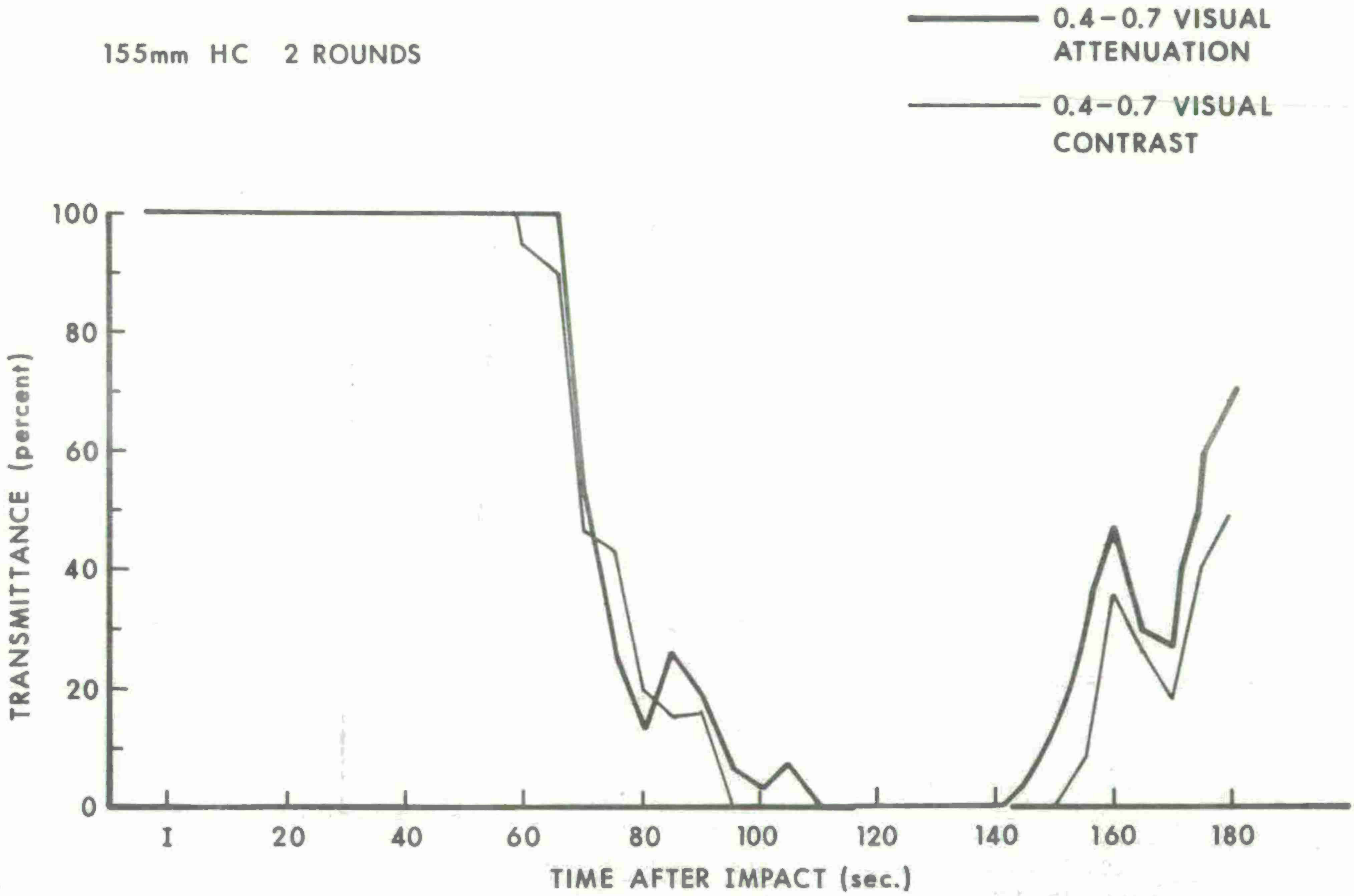

Figure 17 Visual Transmittance and Visual Contrast Measurements Through 155mm HC Smoke

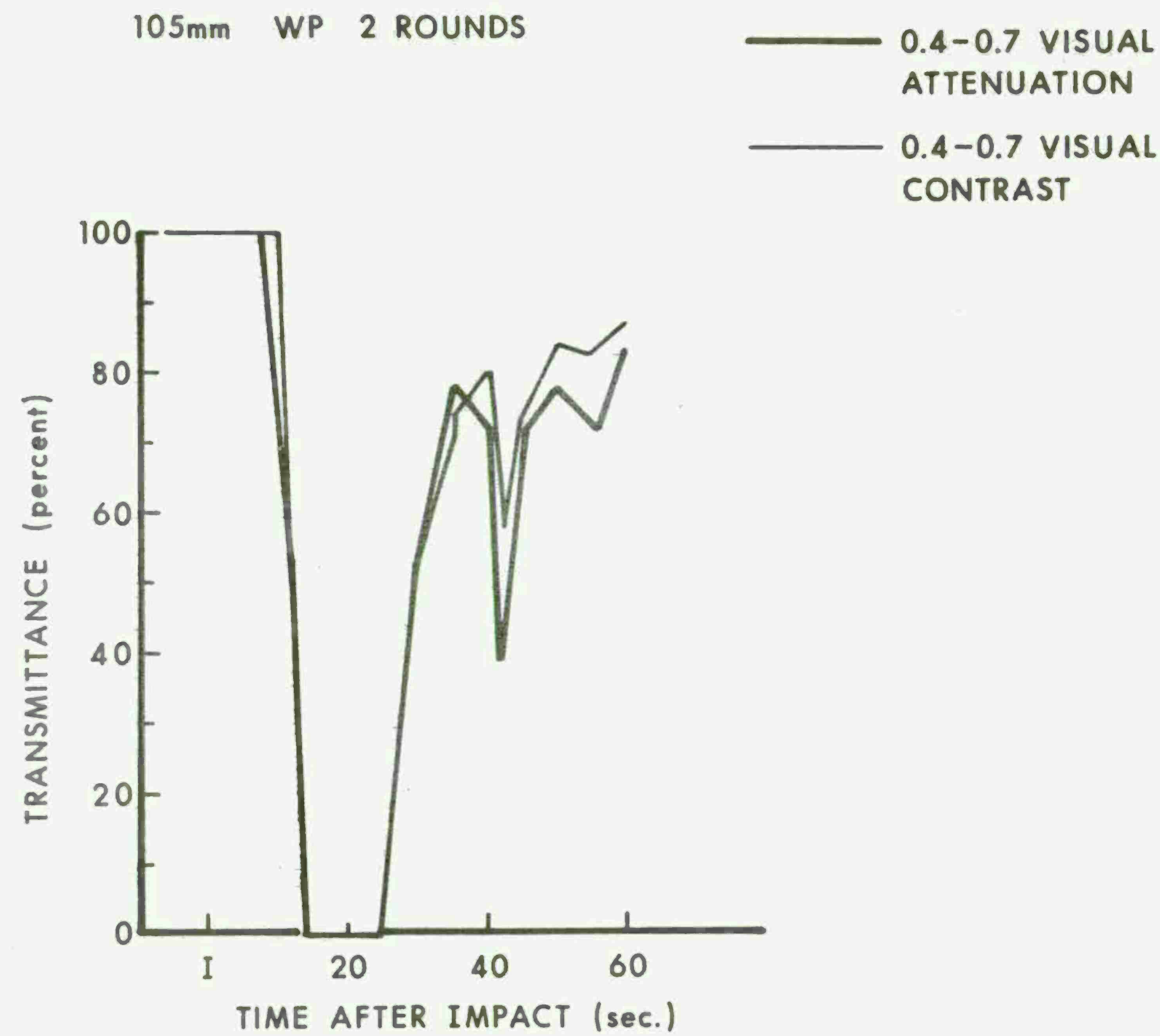

Figure 18 Visual Transmittance and Visual Contrast Measurements Through 105mm WP Smoke

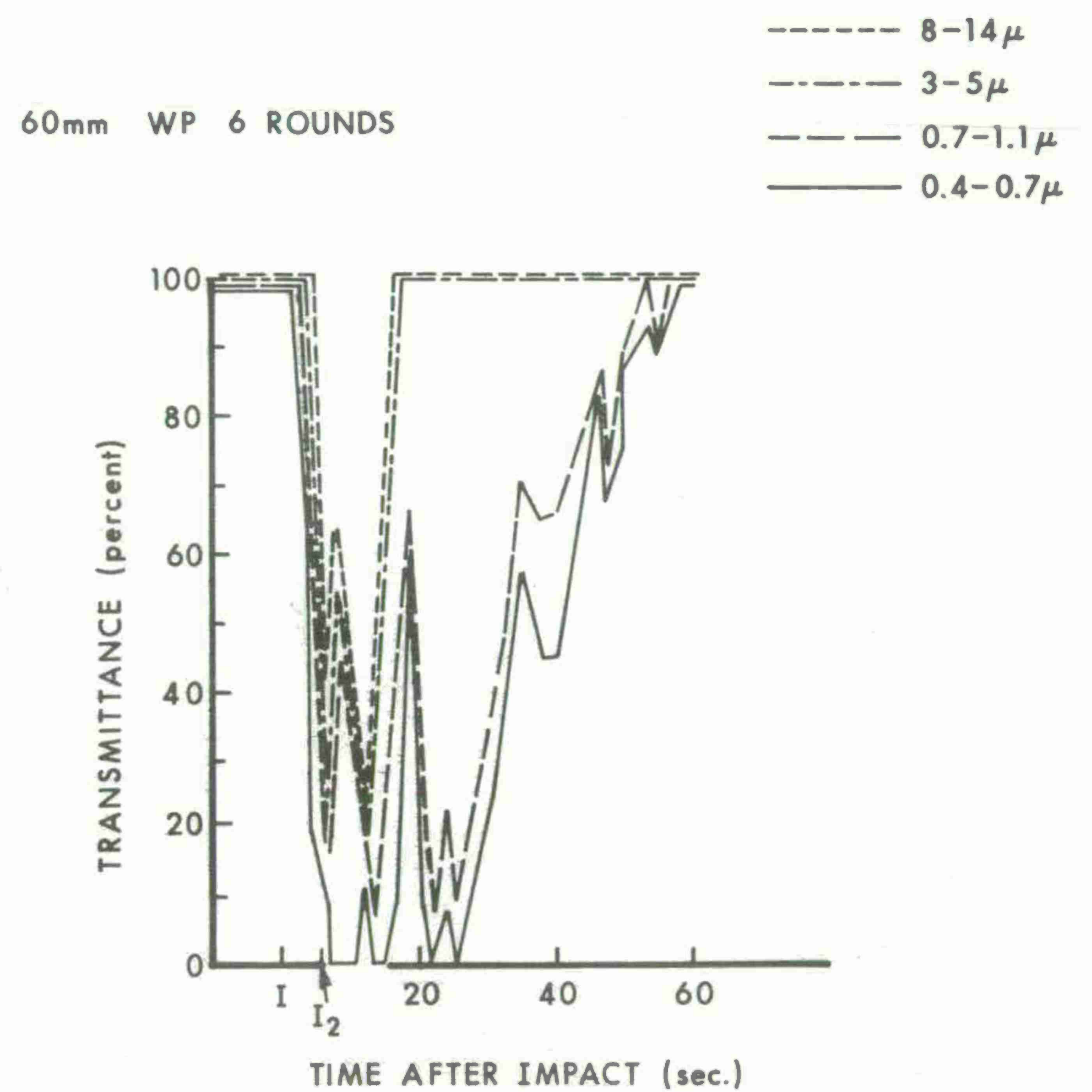

Figure 19 Transmittance Measurements Through 60mm WP Smoke

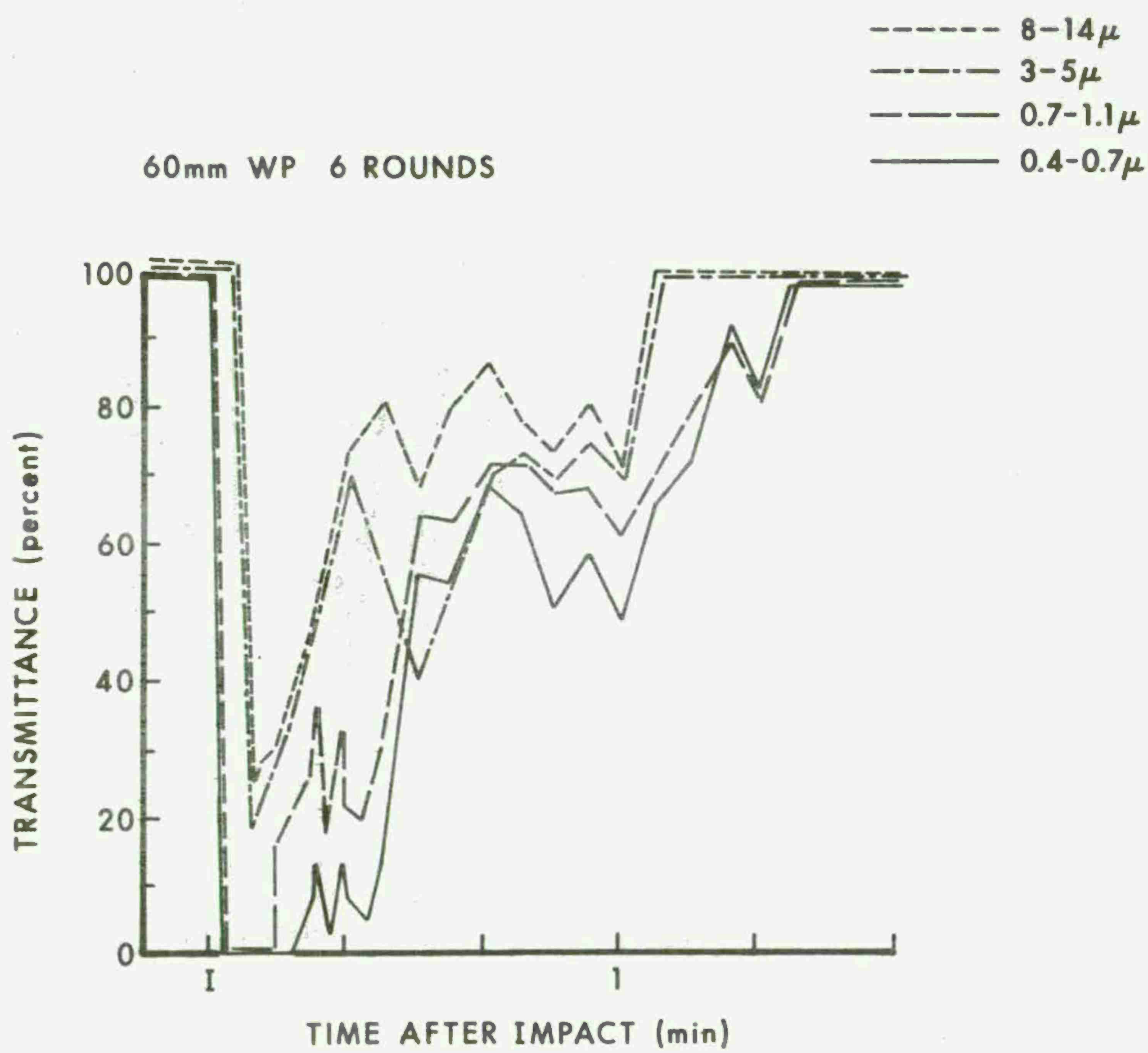

Figure 20 Transmittance Measurements Through 60mm WP Smoke

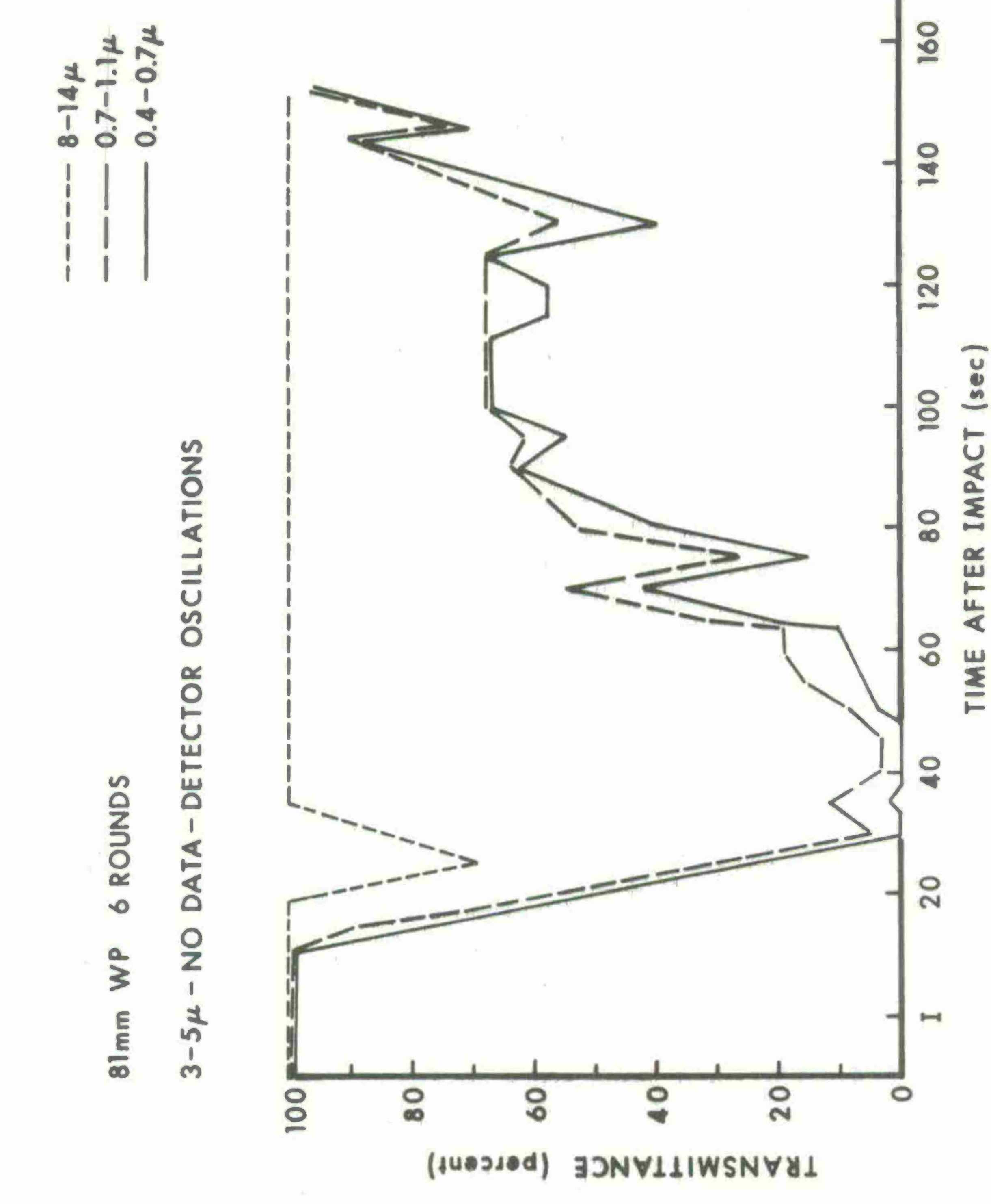

Figure 21 Transmittance Measurements Through 81mm WP Smoke

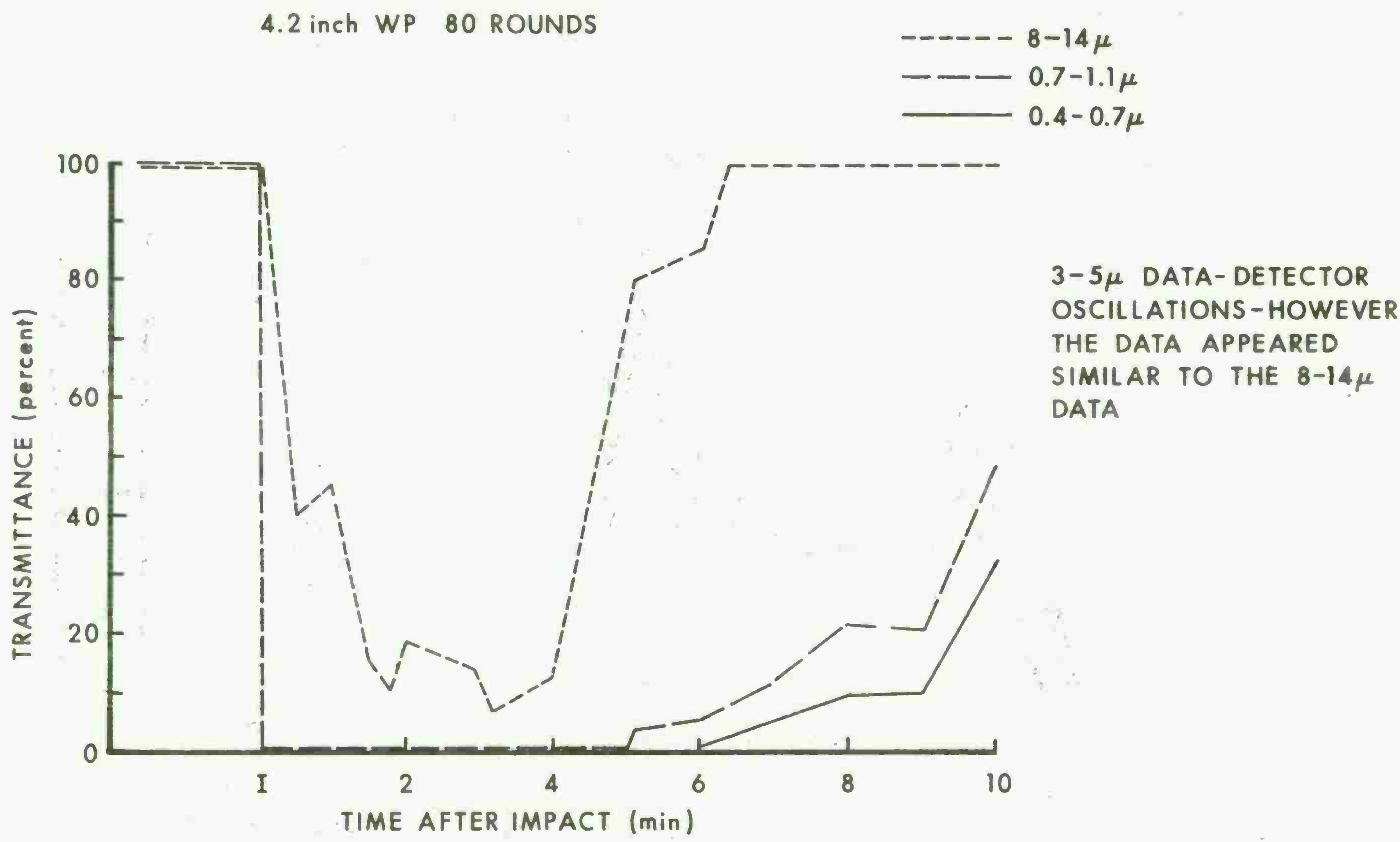

Figure 22 Transmittance Measurements Through 4.2 Inch WP Smoke

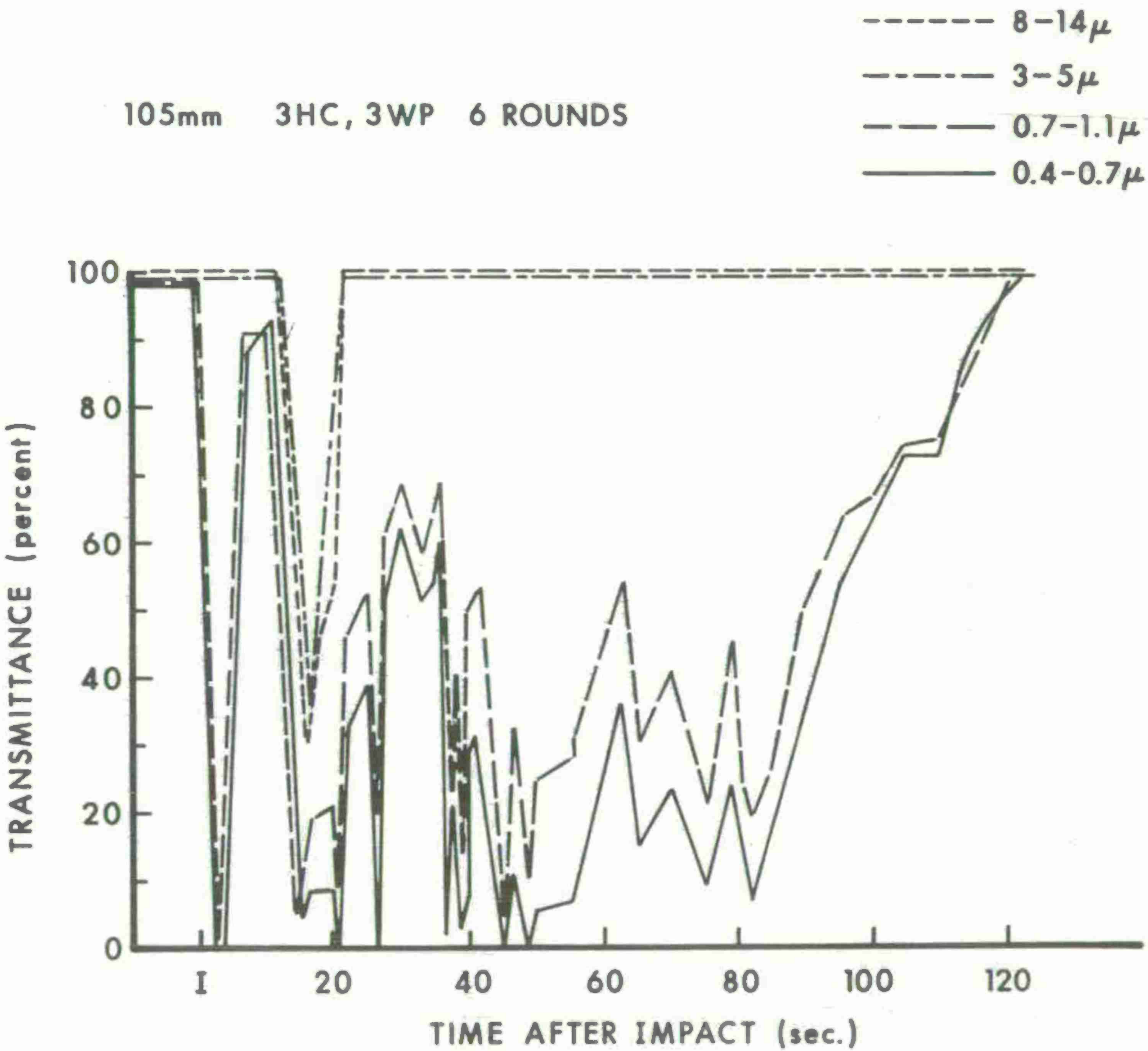

Figure 23 Transmittance Measurements Through 105mm HC, WP Smoke

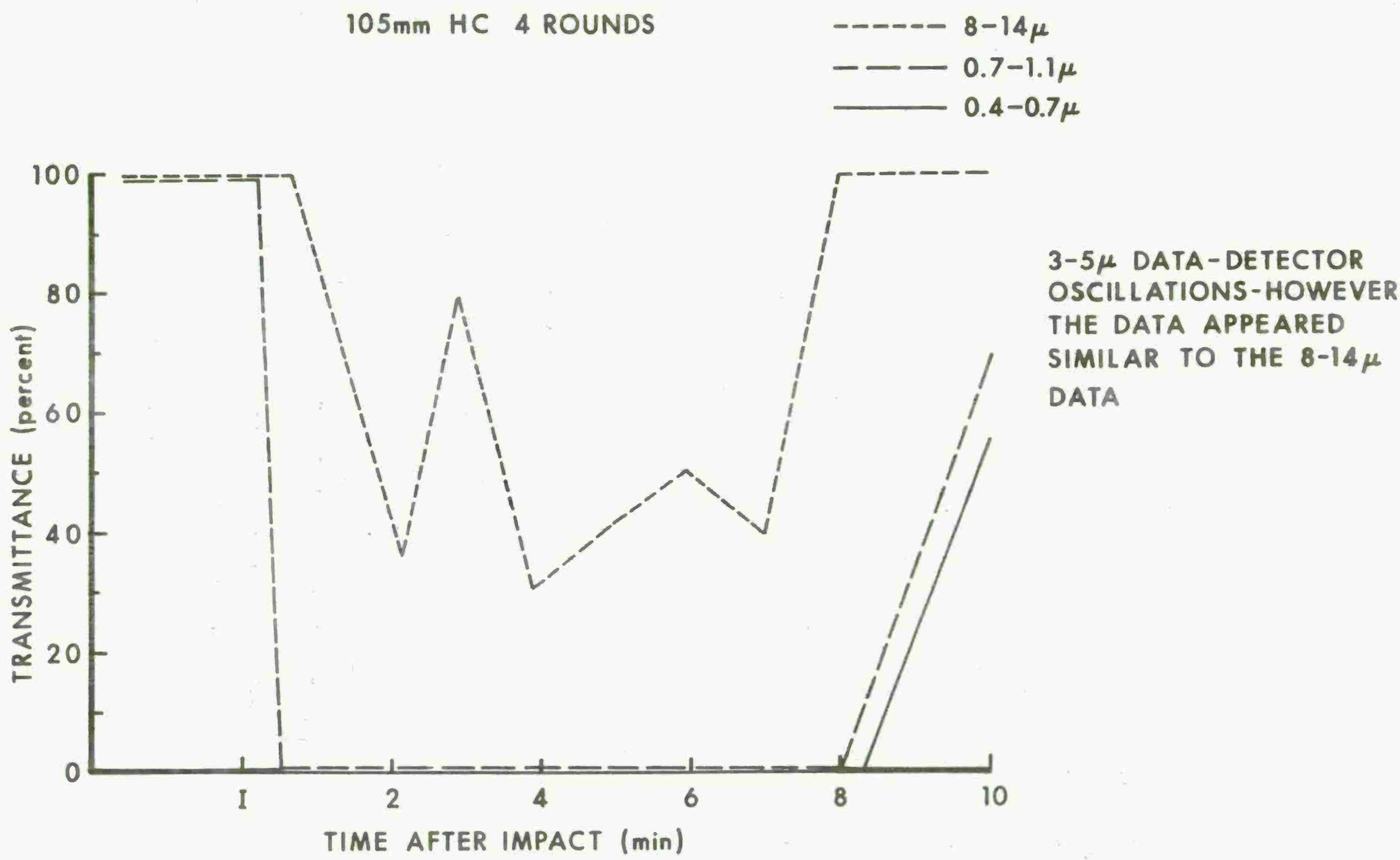

Figure 24 Transmittance Measurements Through 105mm HC Smoke

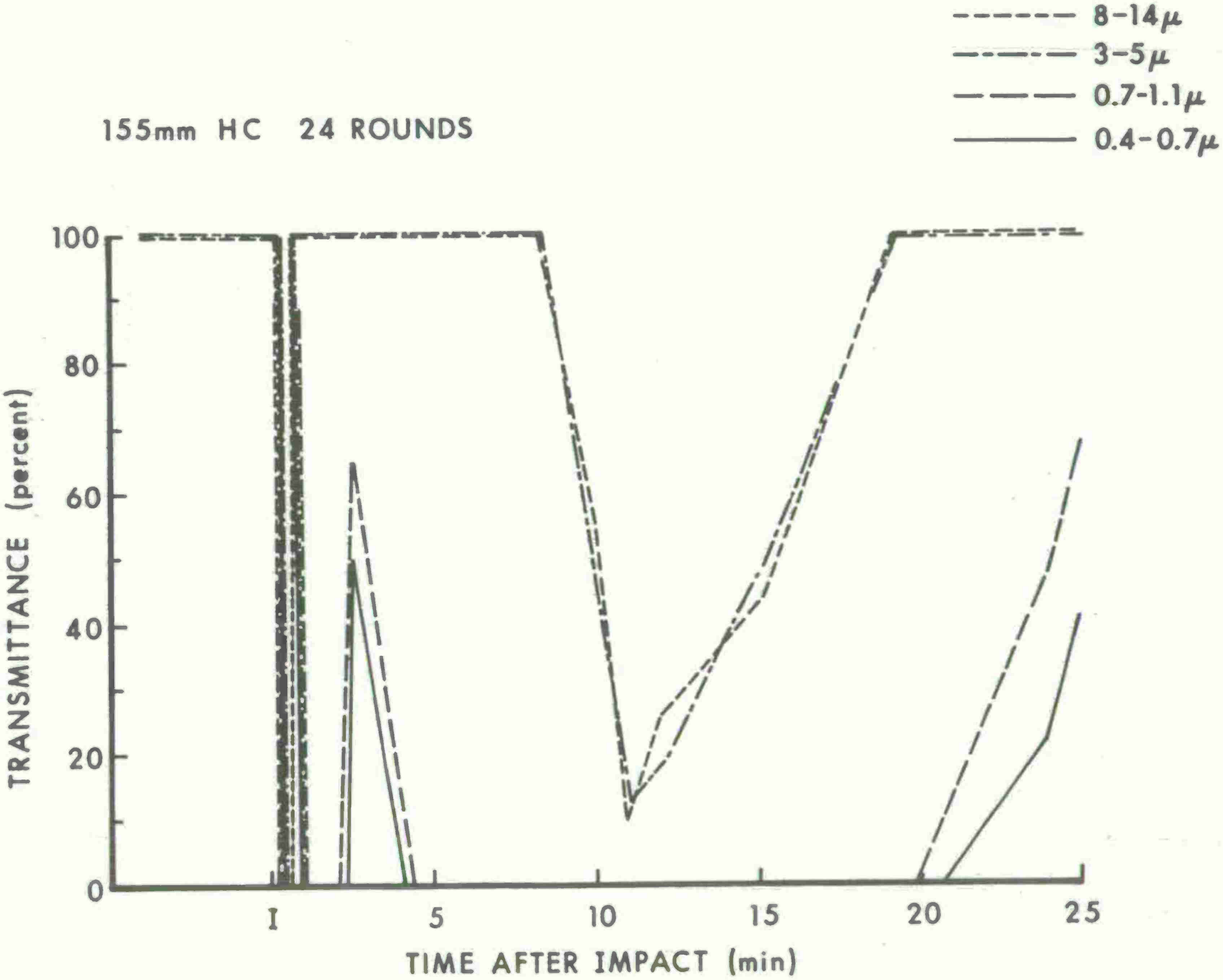

Figure 25 Transmittance Measurements Through 155mm HC Smoke

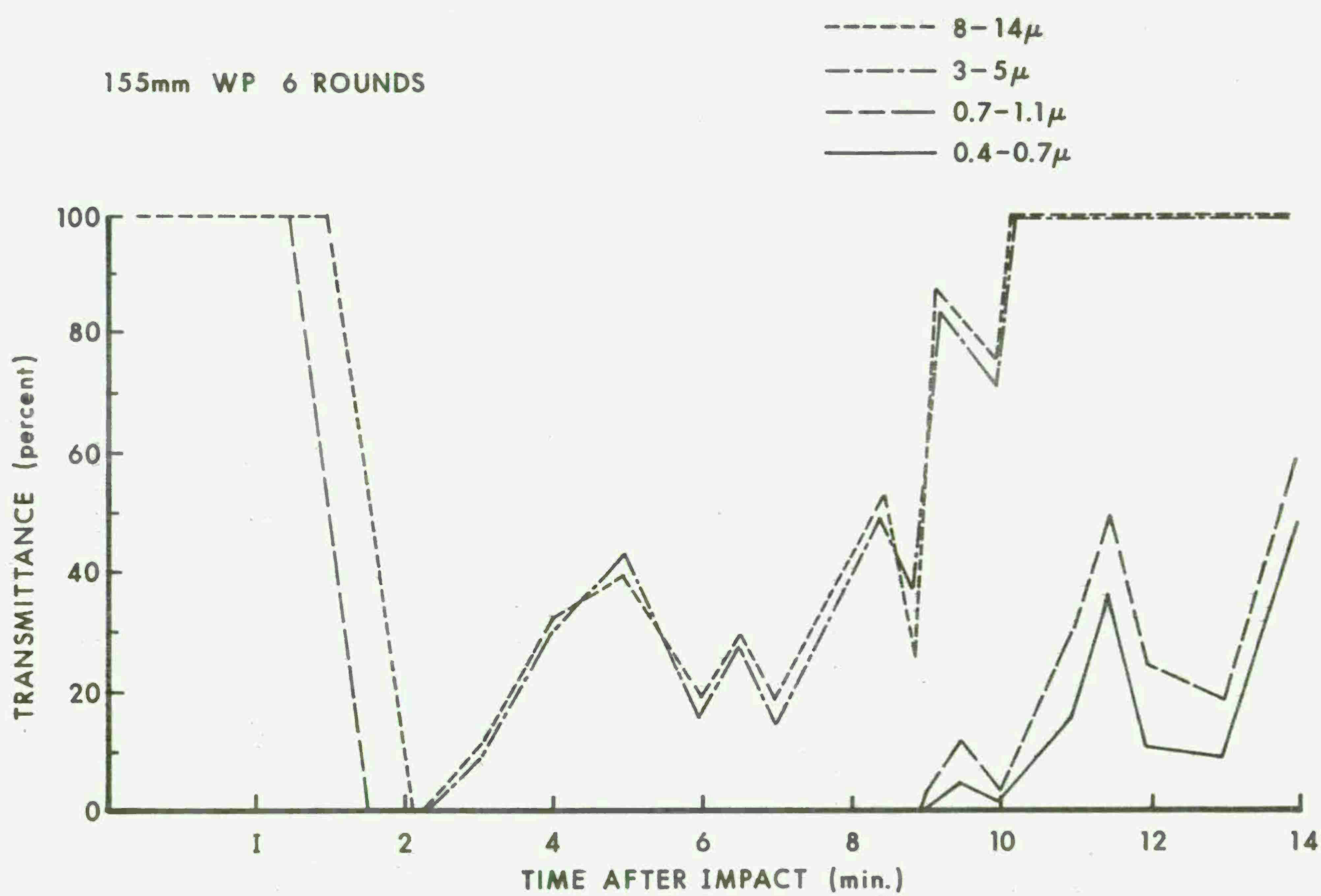

Figure 26 Transmittance Measurements Through 155mm WP Smoke at Night.

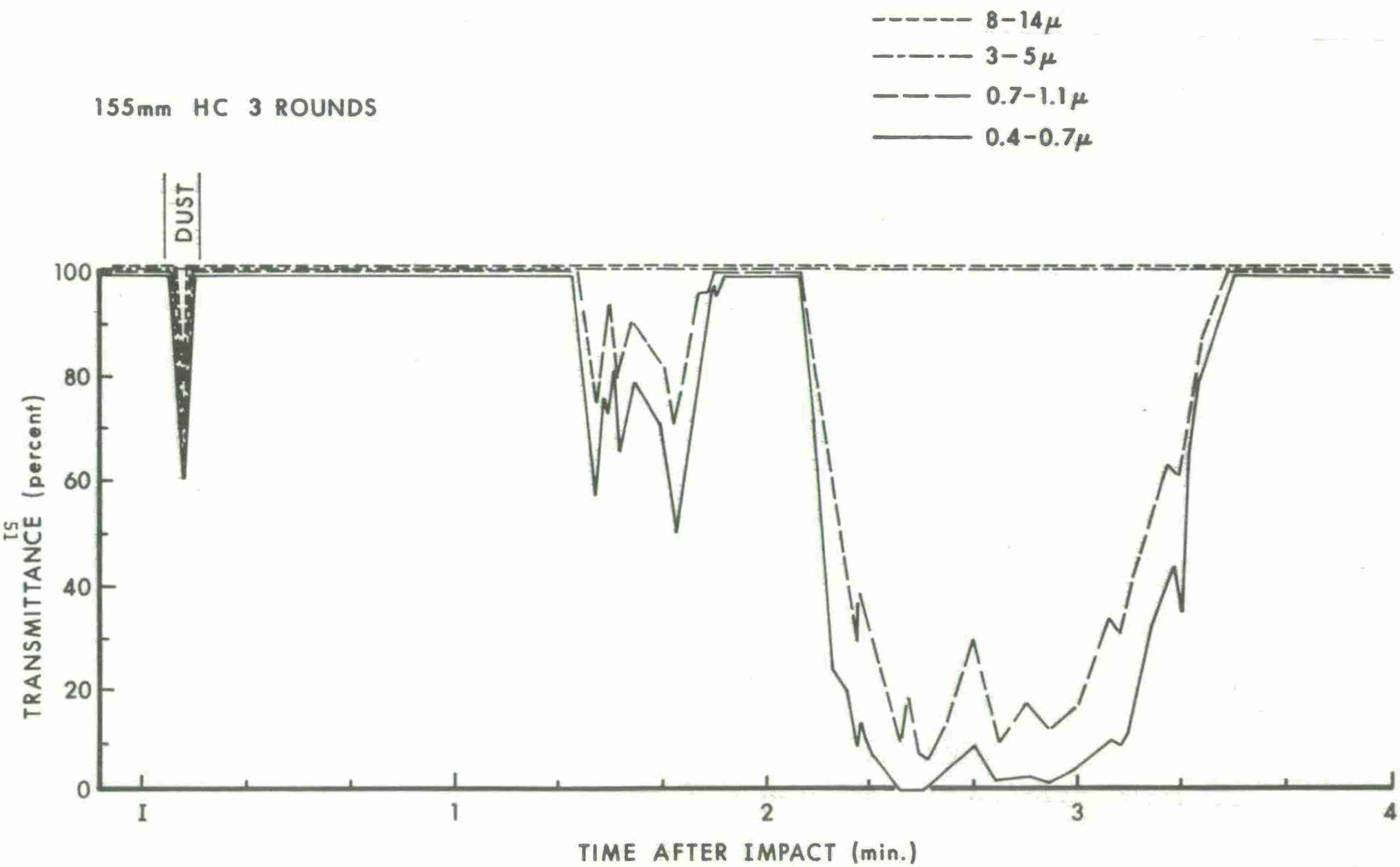

Figure 27 Transmittance Measurements Through 155mm HC Smoke

	WT OF WP (lb)	MAXIMUM TIME AT 0% TRANSMITTANCE (MINUTES)			
		0.4–0.7μ	0.7–1.1μ	3–5μ	8–14μ
60mm	.76	0.17	0.12	x	x
81mm	1.75	0.42	0.25	x	x
4.2 inch	8.14	12	9	x	x
105mm	4	8	8	x	x
155mm	15.6	17	16	0.17	0.17

x – TRANSMITTANCE NEVER WENT TO 0%

Figure 28 Results of Transmissometer Measurements from the Ft. Sill Smoke Test.

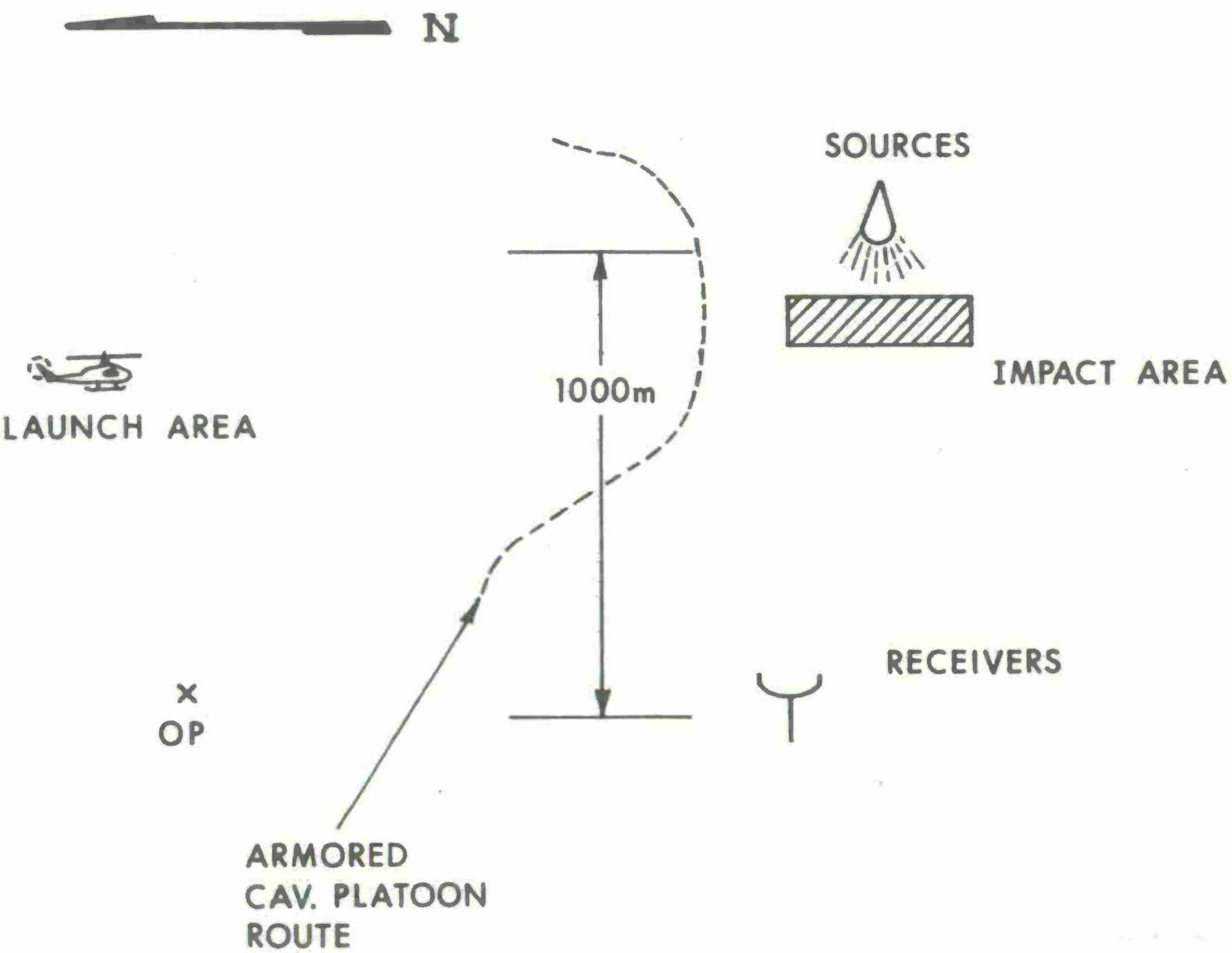

Figure 29 Diagram of the Ft. Hood Smoke Test Range

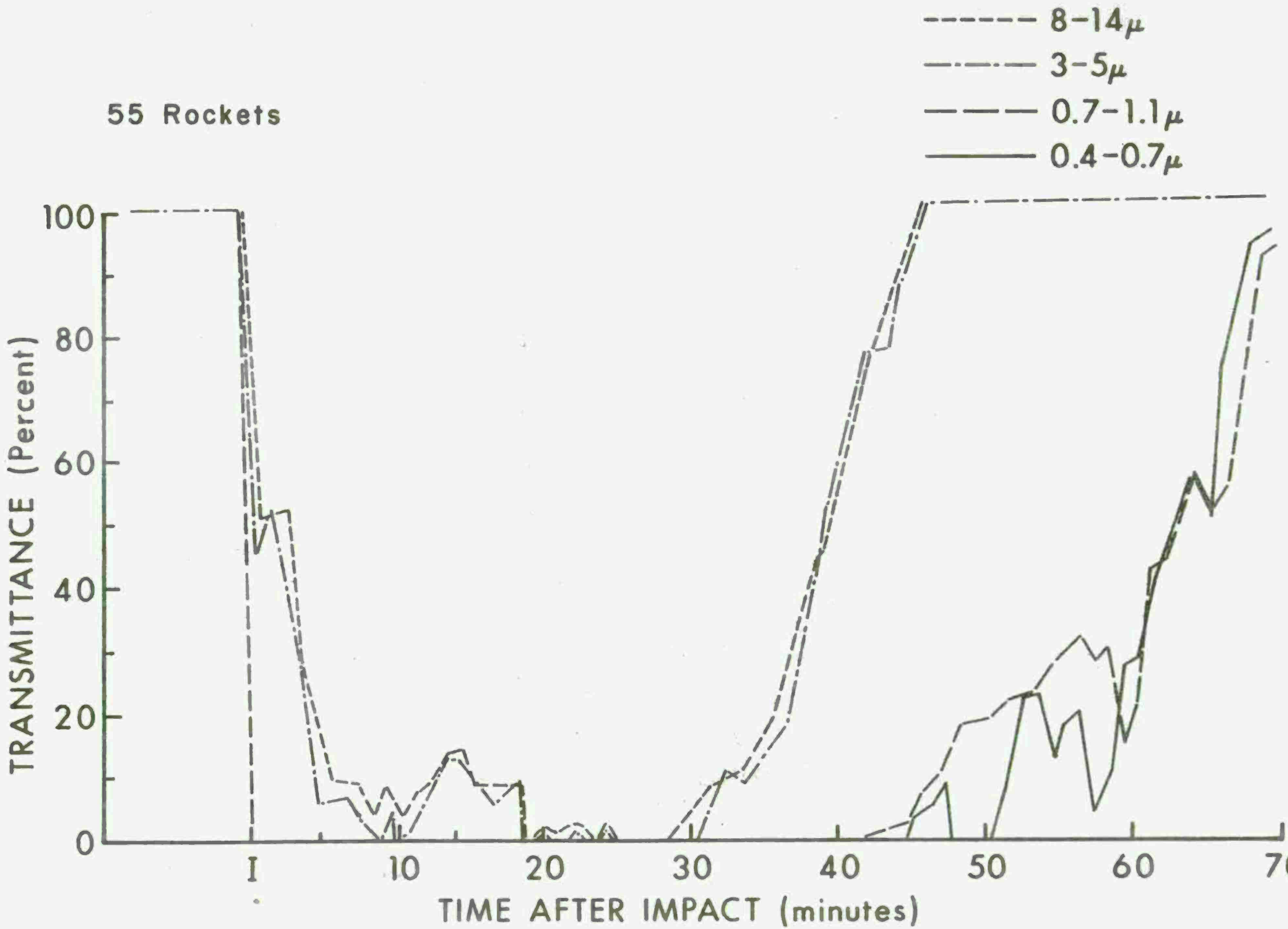

Figure 30 Transmittance Measurements Through 2.75 - Inch WP Wick Rocket Smoke

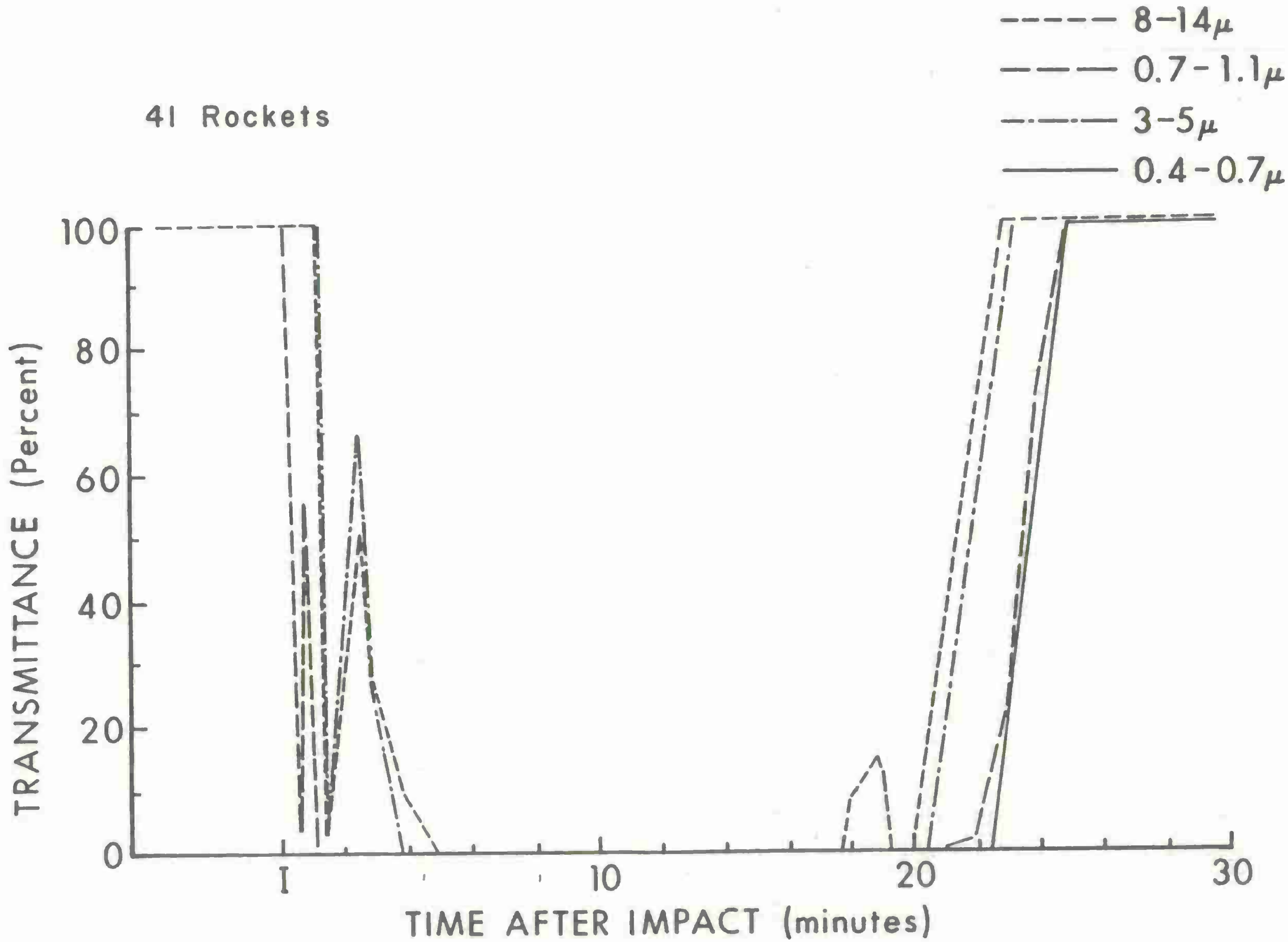

Figure 31 Transmittance Measurements Through 2.75-Inch WP Wick Rocket Smoke

FT. HOOD SMOKE TEST

MAXIMUM TIME AT 0% TRANSMITTANCE (MINUTES)

0.4-0.7μ	0.7-1.1μ	3-5μ	8-14μ
45	43	17	13

Figure 32 Results of Transmissometer Measurements from the Ft. Hood Smoke Test.

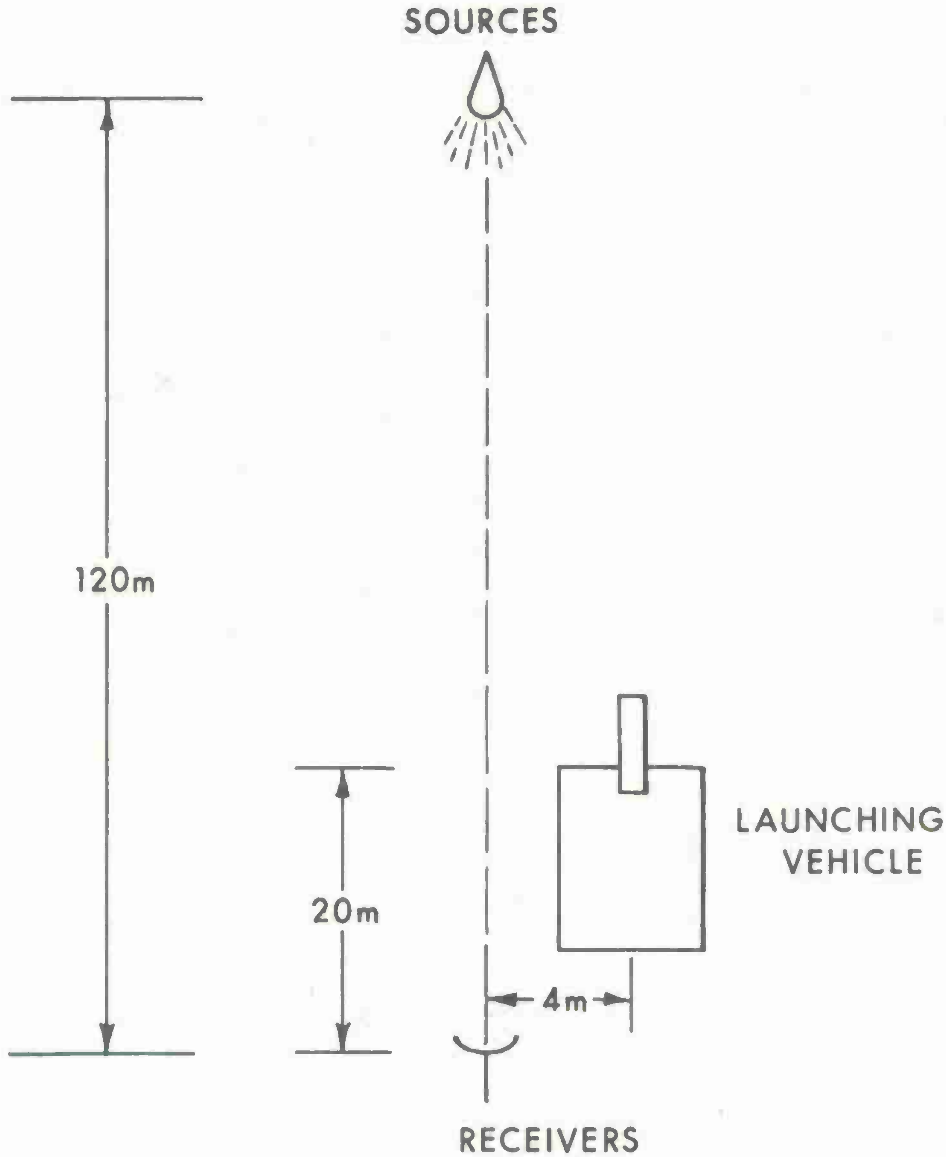

Figure 33 Diagram of Vehicle Grenade Smoke System Test Range

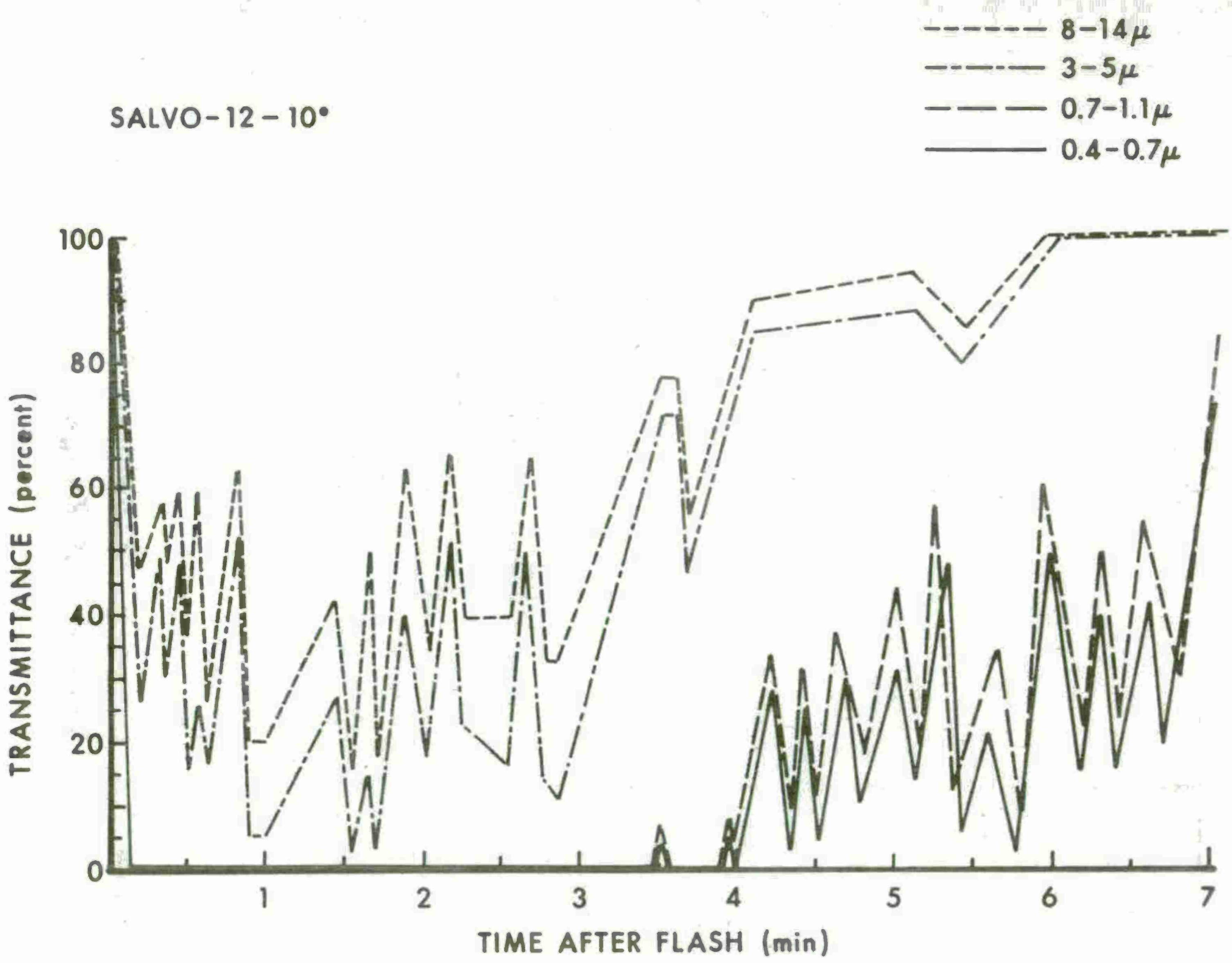

Figure 34 Transmittance Measurements Through Vehicle Grenade Smoke

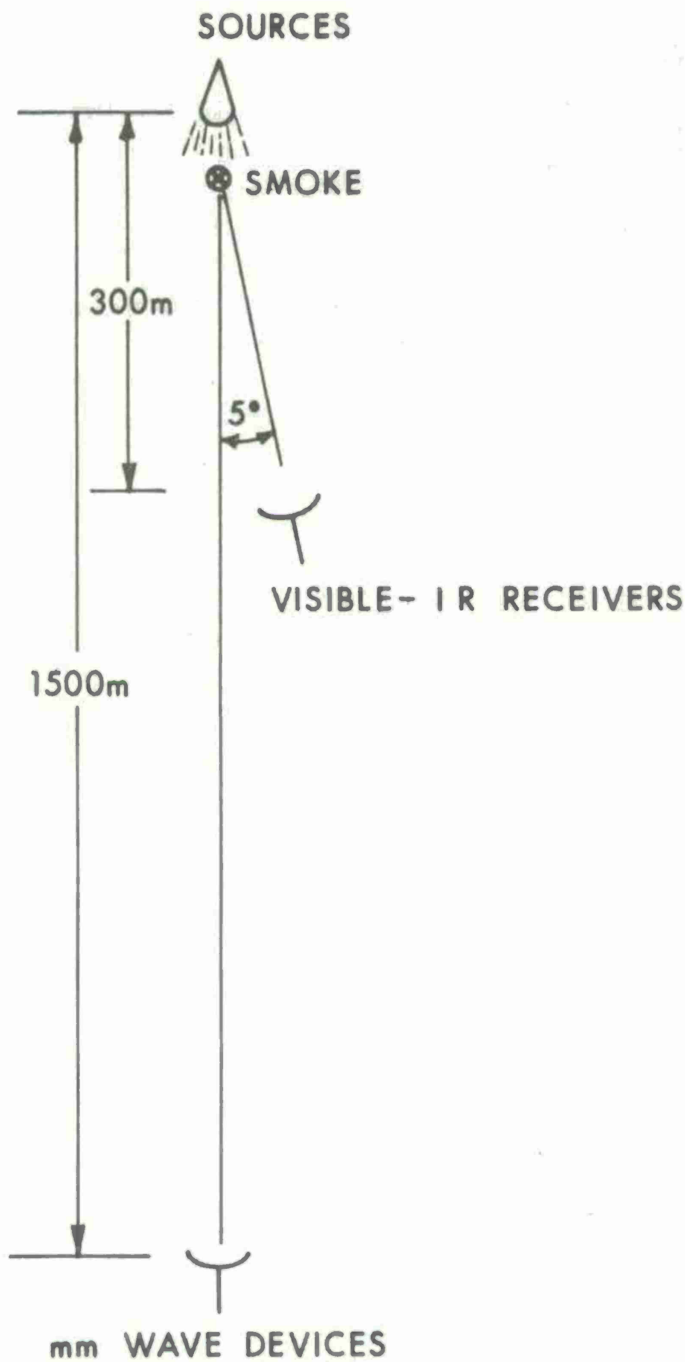

Figure 35 Diagram of Old Bombing Field Smoke Test Range

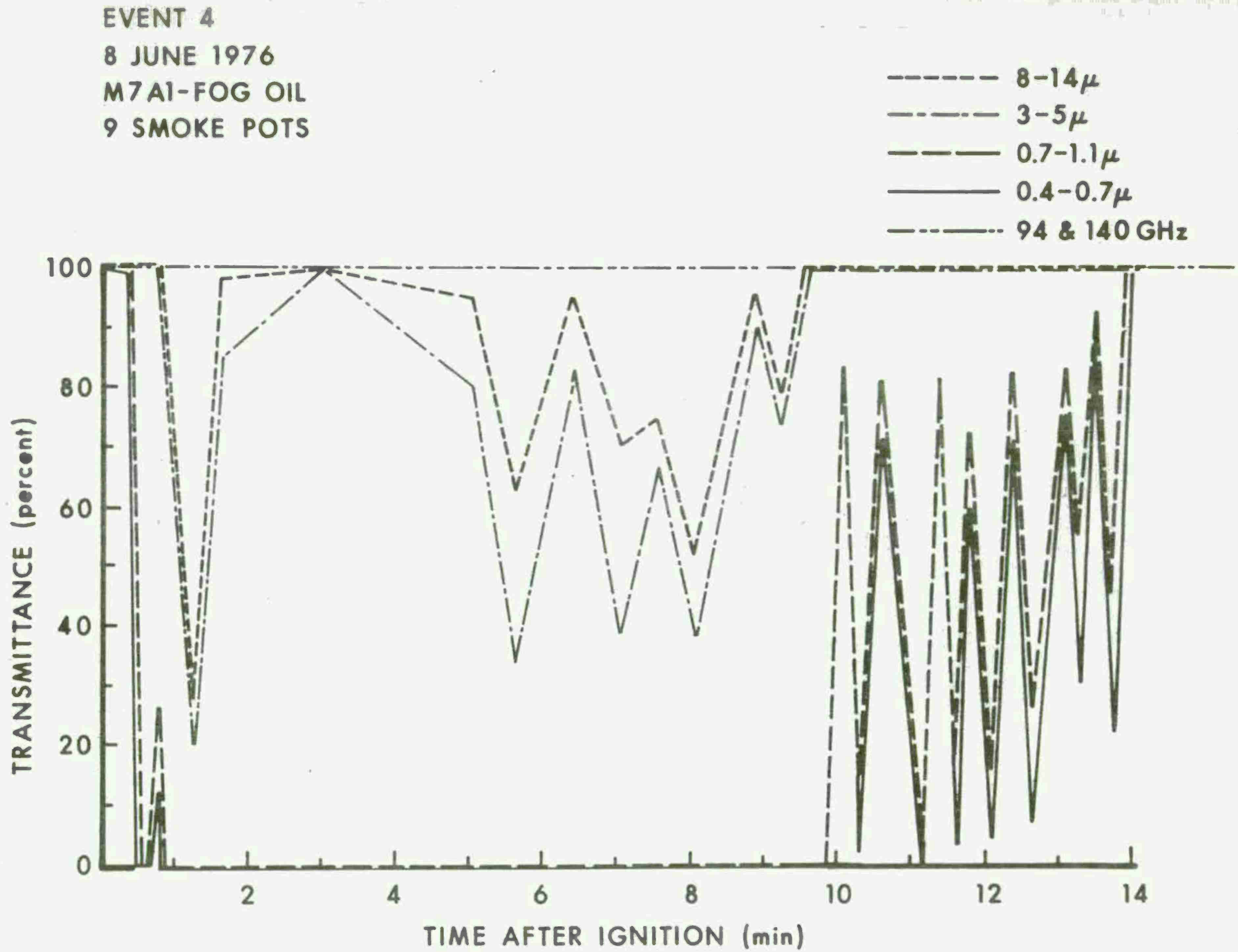

Figure 36 Transmittance Measurements Through Fog Oil Smoke (Pots)

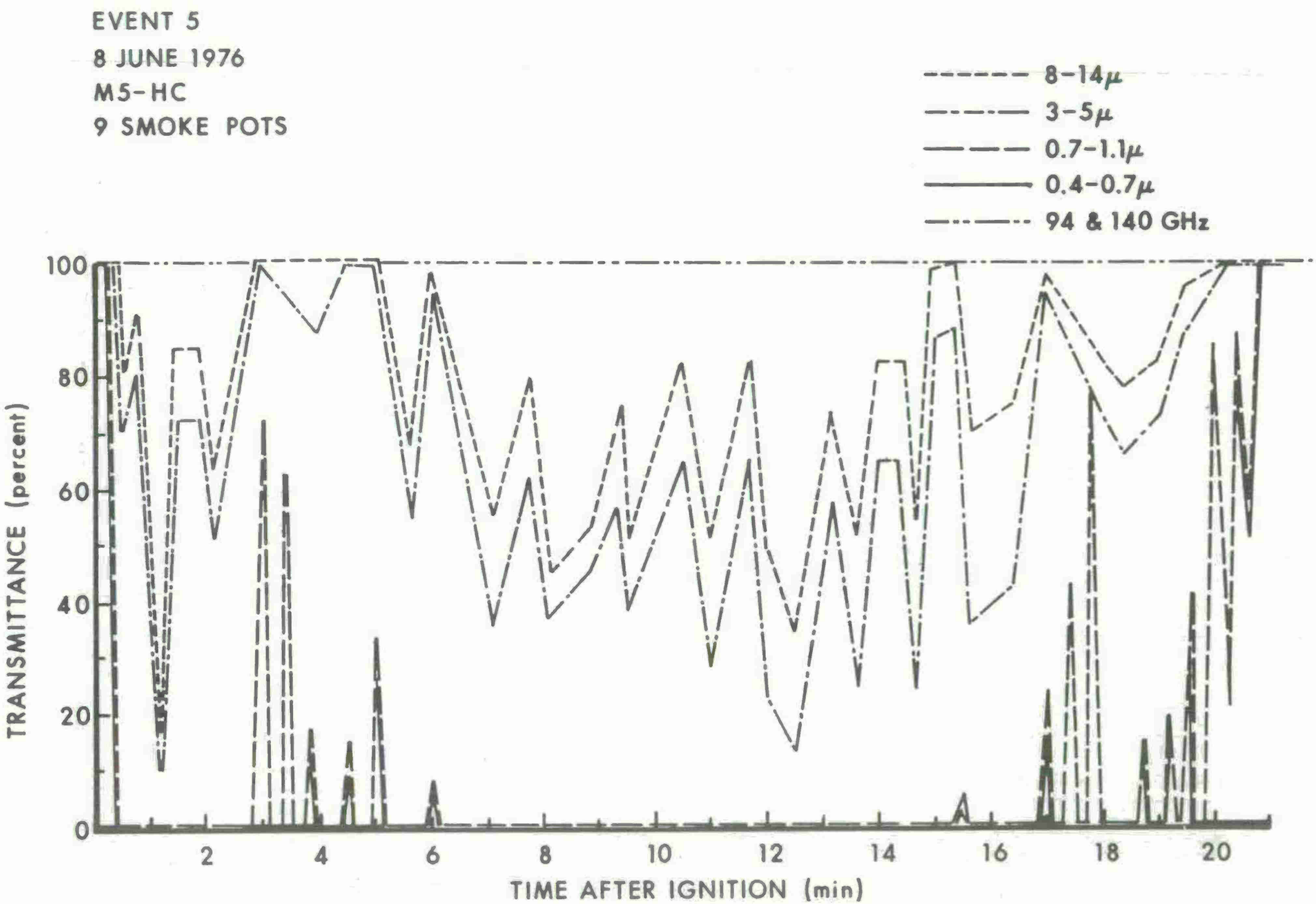

Figure 37 Transmittance Measurements Through HC Smoke (Pots)

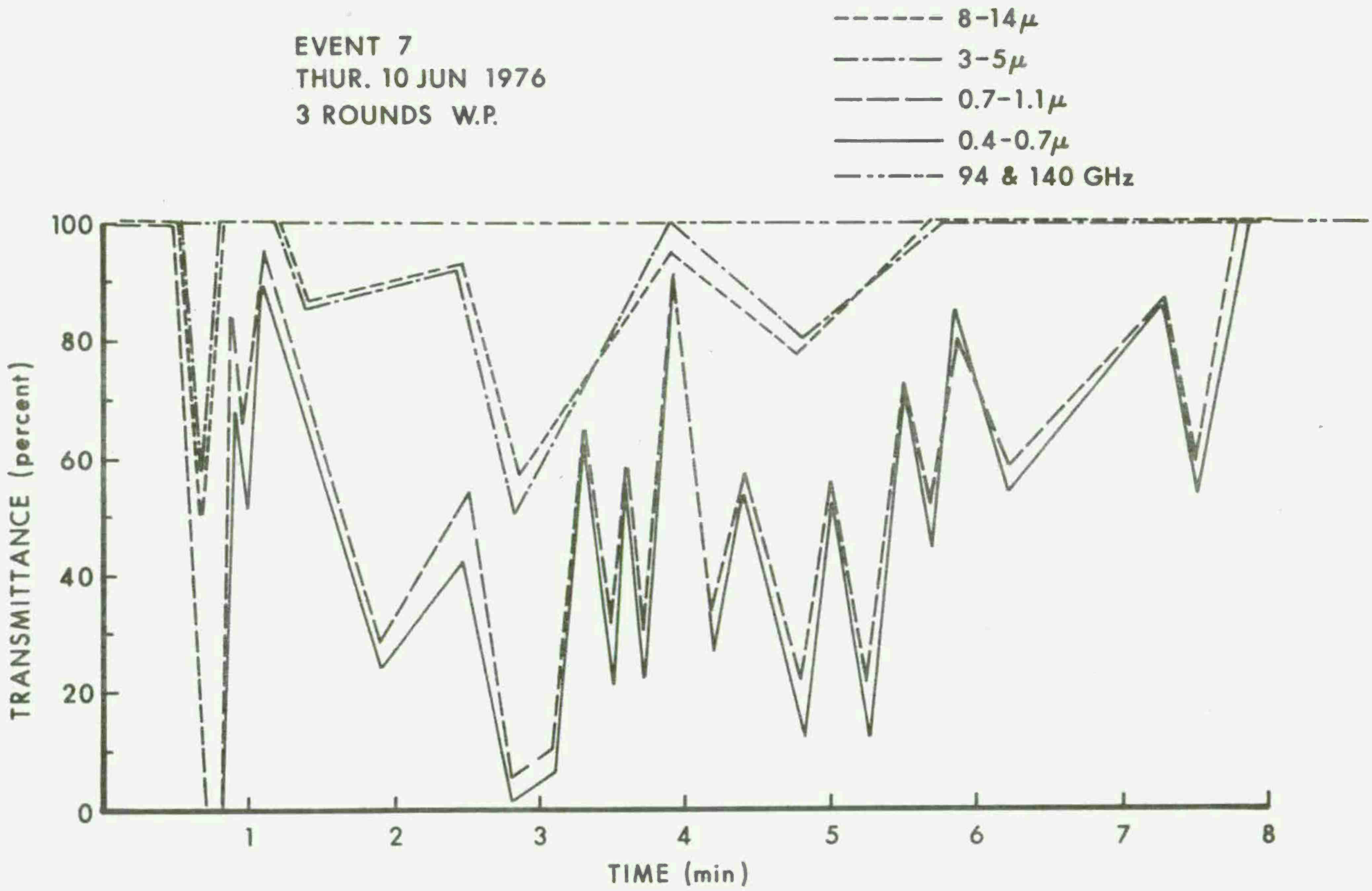

Figure 38 Transmittance Measurements Through 155 mm WP Smoke

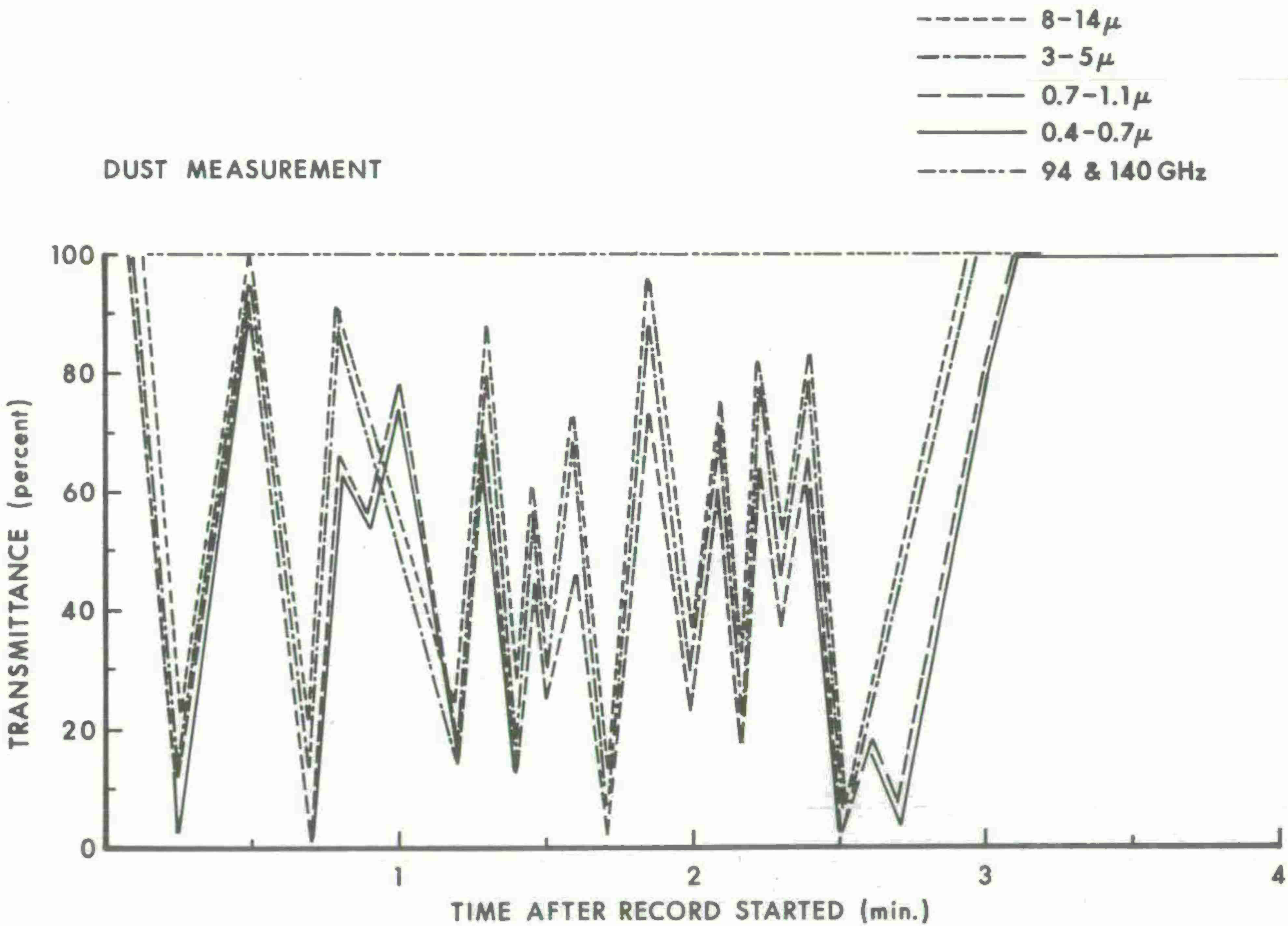

Figure 39 Transmittance Through Dust Clouds

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